Experimental investigations and optimization of the machinability aspects of AISI 4340 alloy steel using uncoated carbide and coated cermet inserts in dry hard turning

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Certificate

This is to certify that the report entitled, **"Experimental investigations and optimization of the machinability aspects of AISI 4340 alloy steel using uncoated carbide and coated cermet inserts in dry hard turning**" submitted by **Mr. Akash Mukhopadhyay,** Roll No. **213ME2412** in partial fulfillment of the requirements for the award of **Master of Technology** in **Mechanical Engineering** with **"Production Engineering"** Specialization during session 2014-2015 in the Department of Mechanical Engineering in National Institute of Technology Rourkela, is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in this report has not been submitted to any other University/Institute for award of any Degree or Diploma.

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Abstract

Comparisons were made between the performances of uncoated carbide and coated cermet inserts for various machinability aspects during machining of hardened alloy steel (AISI 4340, 48 HRC) under dry cutting environment. Spindle speed, feed and depth of cut were considered as major governing parameters. Workpiece surface temperature, machining forces and tool flank wear were taken as measures to compare the performance estimation of different cutting inserts in this work. All the three input variables were observed to have influence over workpiece surface temperature, feed and radial force in case of both carbide and cermet. The machining operations can be performed at a higher spindle speed without compromising results when cermet inserts are used. Cermets exceeded the performance of carbides for flank wear, cutting force and workpiece surface temperature, though carbides outperformed cermets regarding feed and radial force. The depth of cut was found to be the most significant when feed and cutting forces were concerned, while it was true for radial force using carbides. Speed affected workpiece surface temperature and flank wear for carbides the most, meanwhile this was same when considering radial force with cermets. Feed was the most important parameter while the flank wear of cermets were taken in to account.

Keywords: Cutting forces; Flank wear; Hard turning; Hardened alloy steel; Surface temperature of workpiece

Nomenclature

ANOVA	Analysis of variance
AISI	American Iron and Steel Institute
CVD	Chemical Vapour Deposition
d	Depth of cut (mm)
DF	Degree of freedom
f	Feed (mm/rev)
F_x	Axial / Feed force (N)
F_y	Thrust / Radial force (N)
F_z	Tangential / Cutting force (N)
HRC	Rockwell hardness in C scale
K_r	Entering angle/ Approach angle
L	Machining length (mm)
MQL	Minimum Quantity Lubrication
MS	Mean square
N	Spindle speed (rpm)
Pe	Peclet number
PVD	Physical vapour deposition
r	Nose radius (mm)
R-Sq	Coefficient of multiple determination
SAE	Society of Automotive Engineers
SEM	Scanning Electron Microscope
SS	Sum of squares
T	Workpiece surface temperature (°C)
v	Cutting speed (m/s)
VBc	Flank wear of the inserts (mm)
α	Thermal diffusivity (m^2/s)
α_o	Clearance angle
γ_0	Rake angle

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CHAPTER 1

INTRODUCTION

The achivement of high quality, in terms of workpiece dimensional accuracy, surface finish, high production rate, less wear on the cutting tools, economy of machining in terms of cost saving and to increase the performance of the product with reduced enviornmental impact are the main and effective challenges of modern metal cutting and machining industries [1-3]. Traditionally, hardened steels are machined by grinding process due to their high strength and wear resistance properties but grinding operations are time consuming and limited to the range of geometries to be produced. In recent years, machining the hardened steel in turning which uses a single point cutting tool has replaced grinding to some extent for such application. This leads to reduce the number of setup changes, product cost and ideal time without compromising on surface quality to maintain the competiveness [4,5].

1.1 Metal cutting

Metal cutting is one of the most important methods of removing unwanted material in the production of mechanical components. Metal cutting is a machining process in which a finished surface of desired size, shape, accuracy or finish is obtained by separating the excess layers of material in the form of chips with the aid of a wedge shaped device called cutting tool. The process of metal cutting is affected by a relative motion between the work pieces held against the hard edge of a cutting tool. Metal cutting is a forming process taking place in cutting system components that are so arranged that by their means the applied external energy causes the purposeful fracture of the layer being removed. This fracture occurs due to the combined stress including the continuously changing bending stress that is the cause of cyclic nature of this process.

The main purpose of the machining operation is to bring the work piece at the required surface quality and geometry and to use the cutting tool with maximum performance during its lifetime. In machining, surface quality is one of the most commonly specified customer requirements in which the major indication of surface quality on machined parts is surface roughness. Surface roughness is mainly a result of process parameters such as tool geometry (nose radius, edge geometry, rake angle, etc.) and cutting conditions (feed rate, cutting speed, depth of cut, etc.

Various machining operations are shown in Fig. 1.1.

Turning Milling Grinding

Fig. 1.1: Machining operations

1.2 Hard turning

In modern industries hard turning is becoming more and more popular, because of several drawbacks in grinding operation. Machining of workpiece having hardness value greater than 45 HRC is considered as hard machining. Hard turning is more preferable over grinding due to less time, cost and energy associated with it.

Dr. Kaoru Ishikawa designed Ishikawa diagram which is utilized to find the association of causes to its effects. Hence it is also called cause and effect diagram. Sub-causes and other subdivisions can be displayed in this diagram making it look alike a fish skeleton. Accordingly, some others name it as Fishbone diagram. A figure is shown above to recognize the cause and effects of quality of hard machined parts. Various causes affecting the hard turning are shown in the form of an Ishikawa cause and effect diagram as shown in Fig. 1.2.

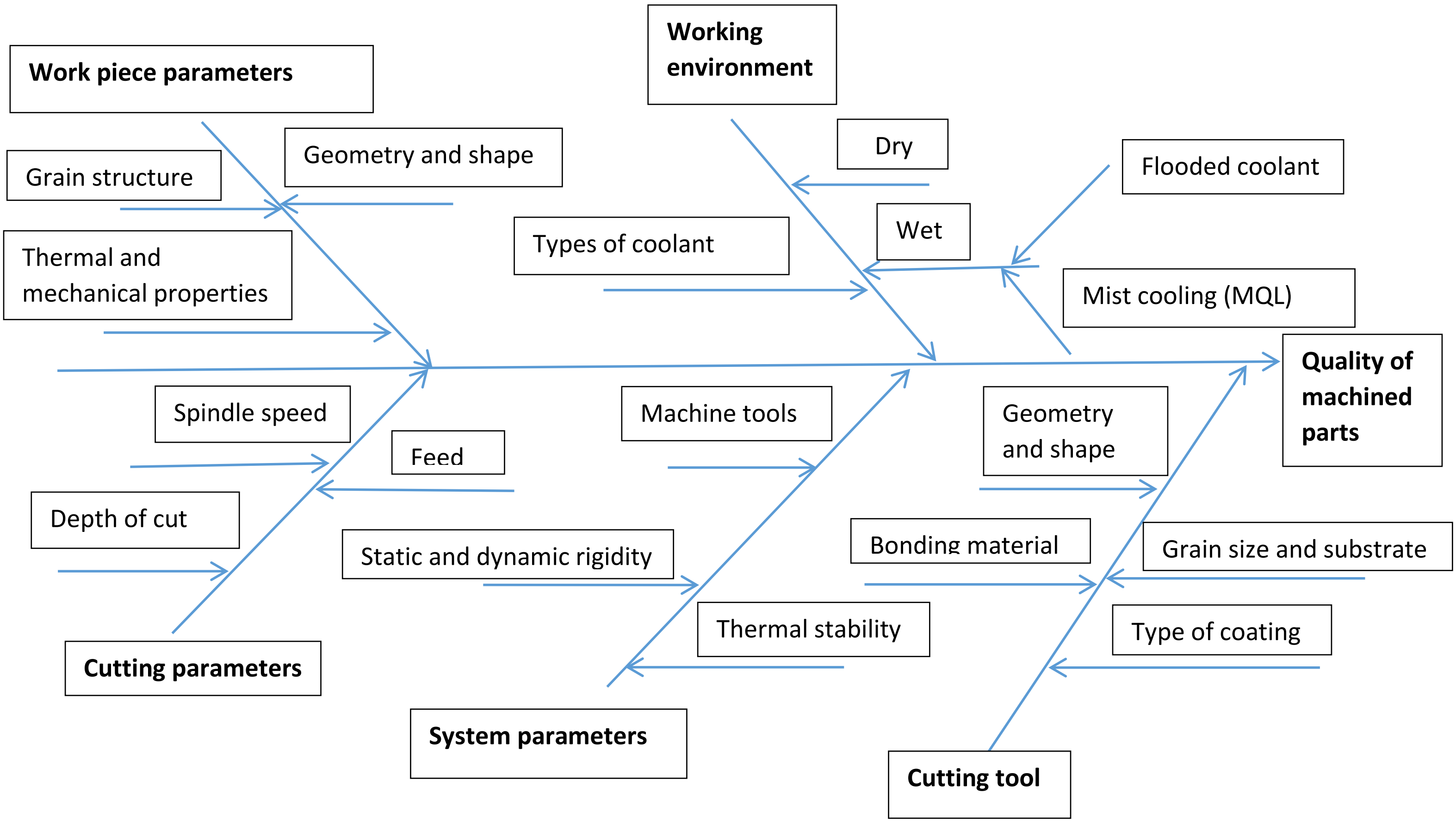


Fig. 1.2: Cause and effect diagram of hard turning

To attain higher productivity during dry hard machining, it is advised to use advanced cutting inserts like carbide, cermet, ceramic, cubic boron nitride (CBN), polycrystalline cubic boron nitride (PCBN), polycrystalline diamond (PCD) etc.

1.3 Dry machining

Dry machining has been considered as the machining of the future to eliminate all the problems associated with the use of cooling lubricants. Now-a-days different authors provided a wide range of examples of successful implementation of dry machining of cast iron, steel, aluminum and even super alloys and titanium. They also expounded that the introduction of dry machining necessitates the adoption of measures suitable to compensate the primary functions of the cooling lubricant and in turn calls for a very detailed analysis of the complex interrelationships linking the process, tool, part and machine tool as shown in Fig. 1.3.

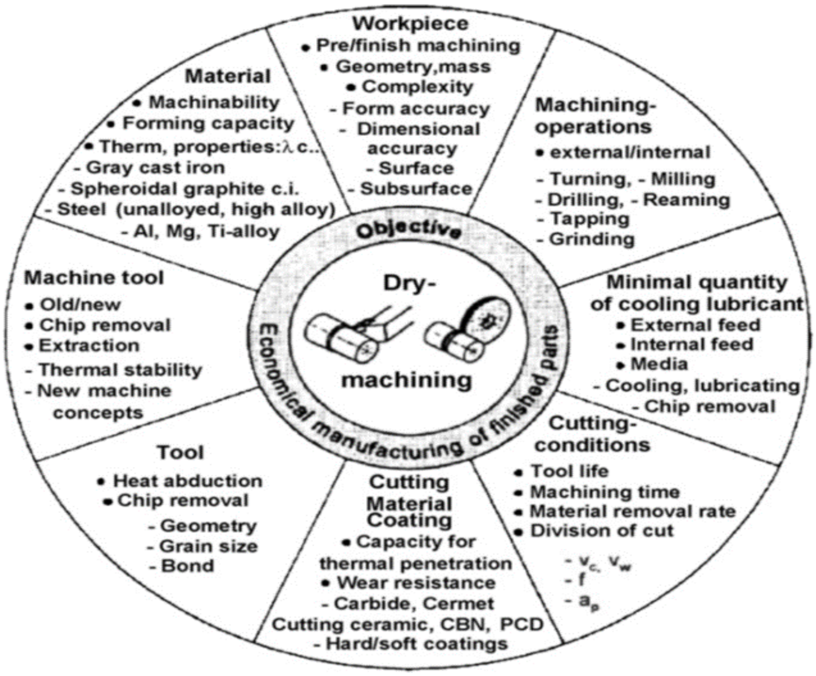


Fig. 1.3: Variables influencing dry machining [6]

1.4 Machinability aspects

The prime target of machining is that its every operation ought to be completed in productive, powerful and monetary way by removing workpiece material at high rate alongside lower utilization of power, tool wear, surface roughness and lower generation of temperature. Henceforth the term machinability can be portrayed as the simplicity with which a workpiece can be machined. However, again the term simplicity is subjective and relative. In machining this can be quantitatively evaluated by measuring parameters like

- Cutting force
- Tool wear
- Temperature
- Vibration
- Power consumption
- Chip morphology, Chip reduction coefficient
- Surface roughness
- Residual stress measurement etc.

1.5 Machining forces

Machining force is likewise one of the significant criteria for deciding the machinability aspect of any workpiece during the machining. The estimation of the cutting forces will help in:

- To determine the power consumption during machining
- To design the machine, fixture and tool system
- To find the effect of various machining parameters on machining forces

1.5.1 Machining forces in turning operation

a) **Cutting force (F_z/F_c) :** It is major component of the resultant force present in the direction of cutting speed and hence called as main cutting force. This force accounts for lower proportion of the resultant force and is used for determination of cutting power consumption.

b) **Axial / Feed force (F_x/ F_t) :** Feed force which acts in the direction of the tool travel. The effect of feed force during machining is of least significant and is generally harmless.

c) **Radial / Thrust force (F_z / F_r) :** The thrust force acts in the direction perpendicular to the machined surface. This force is higher in magnitude but it actuates vibration during machining and dimensional accuracy of machined surface produced.

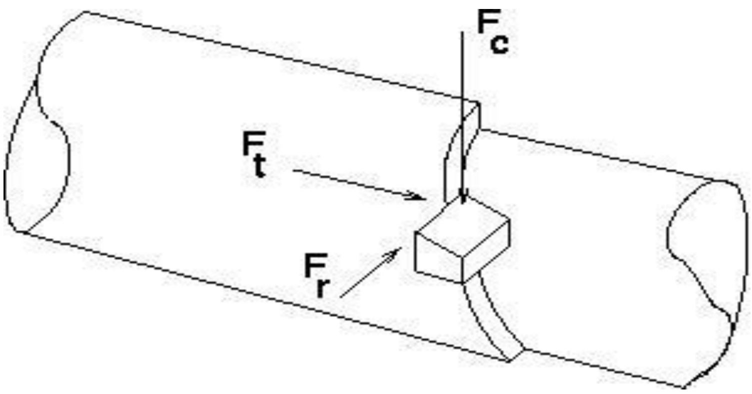


Fig. 1.4: Cutting, feed and thrust force

Various forces and their directions are shown in Fig. 1.4.

1.6 Tool Wear

Tool wear describes the gradual failure of cutting tools due to regular operation. It is the rate at which the cutting edge of a tool wears away during machining. Tool wear causes the tool to lose its original shape. So that in time the tool ceases to cut efficiently or even fails completely. After a certain degree of wear, the tool has to be sharpened for further use. Some General effects of tool wear include:

- increased cutting forces
- increased cutting temperatures
- poor surface finish
- decreased accuracy of finished part

Generally two types of major wears are found in the cutting tools such as crater wear and flank wear.

1.6.1 Crater Wear

Crater wear formed on the rake surface of the tool and it begins at a distance from the cutting edge as shown in Fig. 1.5. This form of wear is due to the intimate contact and pressure of the flowing hot chips. Crater wear is characterized by the maximum depth of the crater and the width of the crater formed. The change in length of the crater form is negligible for a particular depth of cut in machining. Crater wear form is restricted to chip-tool contact area. As the crater depth increases and the lip at the cutting edge between the main cutting edge and the crater front becomes small as the crater progresses towards the cutting edge followed by the flank wear, the cutting edge becomes weaker and may lead on to chipping of the cutting edge. Thus crater is often used as an important factor for finding the tool life.

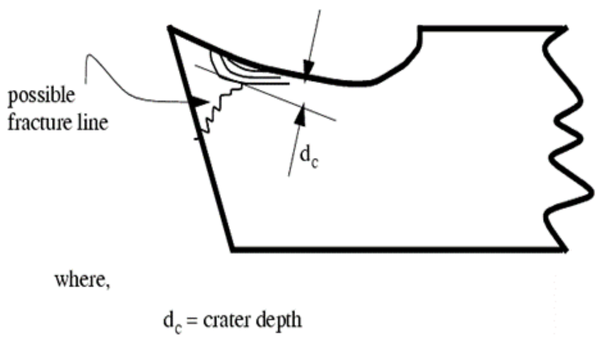


Fig. 1.5: Crater wear

1.6.2 Flank Wear

Wear on the flank (relief) face is called Flank wear and results in the formation of a wear land as shown in Fig. 1.6. Wear land formation is not always uniform along the major and minor cutting edges of the tool. Flank wear most commonly results from abrasive wear of the cutting edge against the machined surface. Flank wear can be monitored in production by examining the tool or by tracking the change in size of the tool or machined part. Flank wear can be measured by using the average and maximum wear land size VB and VB_{max}.

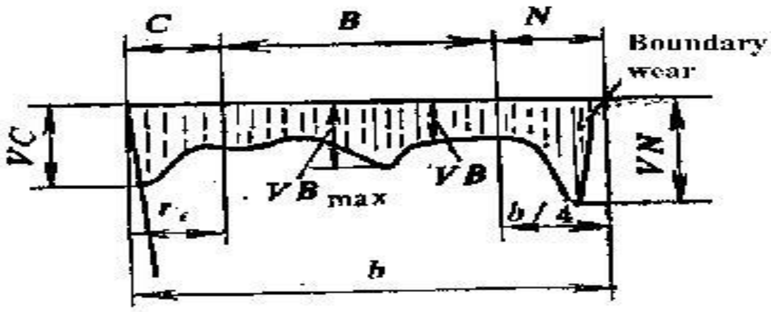
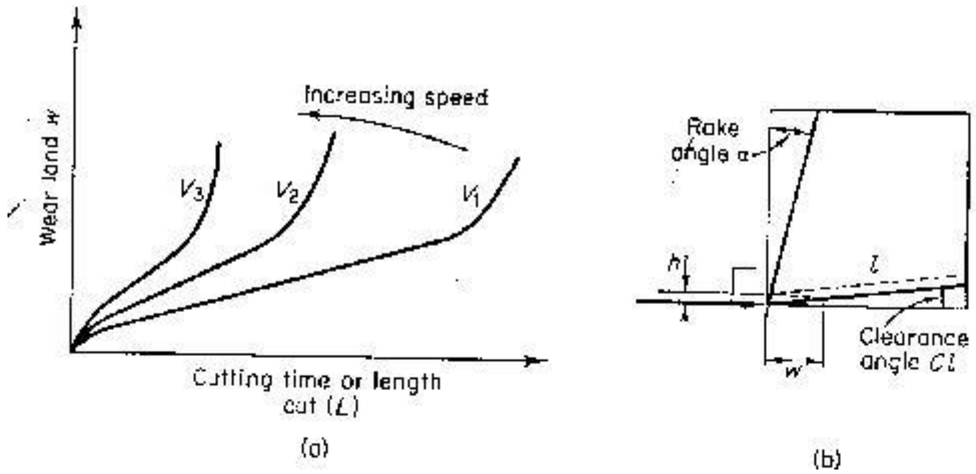


Fig. 1.6: Flank wear region



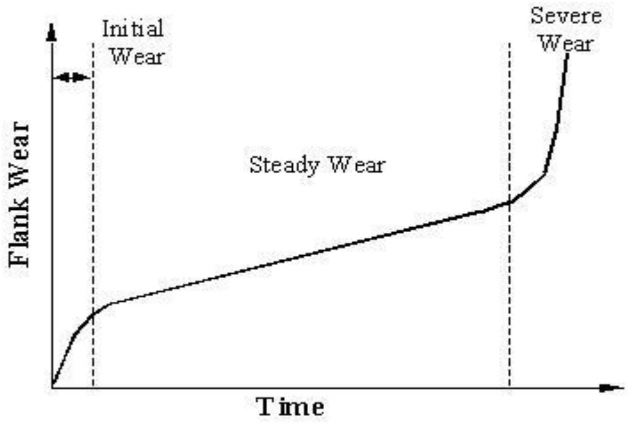


Fig. 1.7: Typical stages of tool wear in normal cutting situation

1.6.2.1 Various regions of Flank Wear

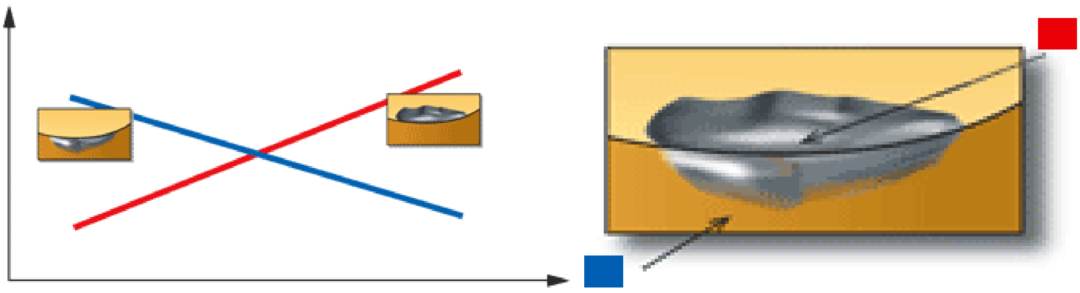
a) Initial (or preliminary) wear region: Caused by micro-cracking, surface oxidation and carbon loss layer, as well as micro-roughness at the cutting tool tip in tool grinding (manufacturing). For the new cutting edge, the small contact area and high contact pressure will result in high wear rate. The initial wear size is VB=0.05-0.1mm normally.

b) Steady wear region: After the initial (or preliminary) wear (cutting edge rounding), the micro-roughness is improved, in this region the wear size is proportional to the cutting time. The wear rate is relatively constant.

c) Severe (or ultimate or catastrophic) wear: When the wear size increases to a critical value, the surface roughness of the machined surface decreases, cutting force and temperature increase rapidly, and the wear rate increases. Then the tool loses its cutting ability. In practice, this region of wear should be avoided.

All the above three regions are shown in Fig. 1.7.

Flank wear and chipping will increase the friction, so that the total cutting force will increase. The component surface roughness will be increased, especially when chipping occurs. Flank wear will also affect the component dimensional accuracy. When form tools are used, flank wear will also change the shape of the component produced. Fig. 1.8 shows development of Crater and flank wear during the working life and affect their finishing performance in different ways.



Cutting speed ›

Flank wear
Crater wear

Fig. 1.8: Cutting speeds affect crater and flank wear differently

1.7 Cutting Temperature

The machining operation is related to generation of high temperature and heat at the zone of machining. The heat created in the machining zone or cutting zone is principally because of plastic deformation of chip or friction produced at work-tool and chip-tool interface. The cutting zone can be partitioned fundamentally into three regions as depicted in Fig. 1.9:

a) **Primary shear zone:**

This is the zone where maximum generation of heat happens almost 60-80 % in view of the plastic or mechanical deformation of the shear zone amid the machining operation. The significant amount of the heat created at this area is taken up by the chip and little by workpiece material.

b) **Secondary deformation zone :**

It is the zone at the chip-tool interface where the heat generation is in the region of 10-15 %. Here the heat delivered is as an after-effect of both mechanical deformation and erosion created because of rubbing activity between the tool and chip, the maximum measure of the heat being diverted by chip.

c) **Tertiary heat zone :**

In this zone the friction between the workpiece and tool interface results in generation of heat which is around 5-10 % of the total heat generation.

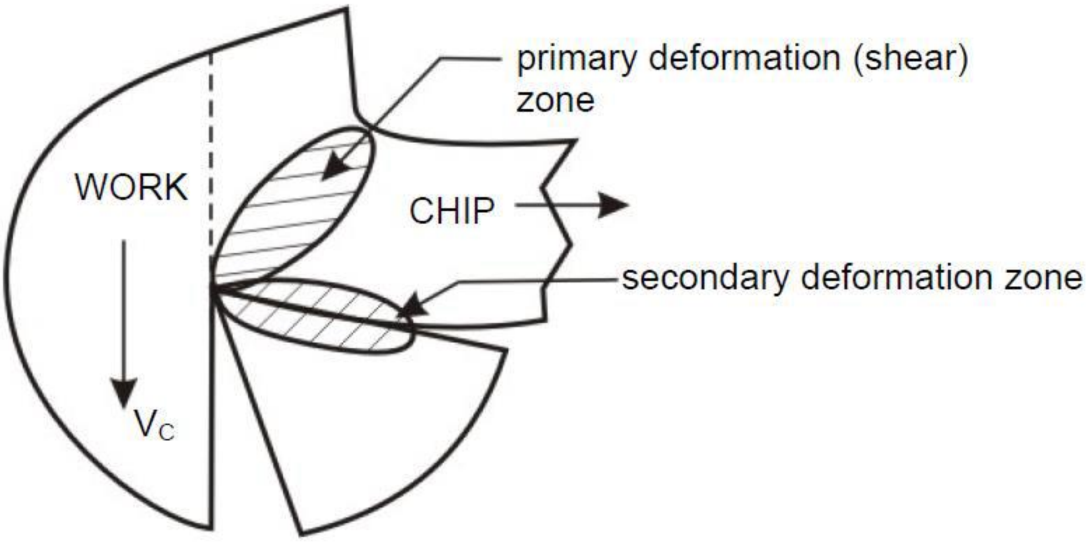


Fig. 1.9: Cutting zones in the chip [7]

1.7.1 Effect of cutting temperature

a) On cutting tool :

Excessive generation of the heat at the chip-tool interface is not favourable and may result in:

- High tool wear rate
- Built-up edge formation
- Fracturing and thermal flaking of the cutting tool edge due to thermal flaking.

b) On surface integrity of workpiece :

The high generation of heat may also affect the machined surface integrity in following manner:

- Generation of white layer due to excessive temperature
- Formation of micro-cracks
- Residual stress (tensile) generation
- Dimensional inaccuracy of the machined material due to thermal distortion.

1.7.2 Cutting temperature measurement

The generation of high temperature and heat at cutting zone decreases the cutting force because of softening of the material however it additionally abbreviates tool life by advancing the tool wear, may bring about dimensional inaccuracy furthermore may degrade the surface quality of the machined surface. So it is vital for evaluating the cutting temperature delivered during machining operation. The cutting temperature can be dictated by two methods below :

a) Experimental Method :

The cutting temperature determined by this method is although difficult but highly accurate and reliable, often expensive method. The experimental method includes following techniques:

- Use of calorimetric set-up
- Optical pyrometer
- Thermocouple principle
- Infrared technique

b) Analytical Method :

Analytical method of determining the cutting temperature includes use of mathematical equations or models which are although much simpler and inexpensive than previous method but with less accuracy.

1.8 Development of Tool Materials

In all machining operations cutting speeds and feed are limited by the capability of the tool material. Speeds and feeds must be kept low enough to provide for an acceptable tool life. If not the time lost in changing tools may outweigh the productivity gains from increased cutting speed. To maintain the above the cutting tool materials must have following properties:

- High hardness for easy penetration into the workpiece.
- High mechanical resistance to bending and compression so that it can withstand cutting forces.

- Resistance to abrasion, diffusion and plastic deformation.
- Resistance to high temperature which would otherwise diminish the qualities enumerated above.

No tool material can have all of those four properties. The uncoated cutting tool materials used in machining operation are: High carbon steel or Plain carbon steel, High speed steel (HSS), cemented carbide tools etc.

1.8.1 High Carbon steel or Plain Carbon steel Tool

Steel containing 0.8 to 1.4 % of carbon was quenched 750-800^{o}C and tempered at 180^{o}-200^{o}C to obtain a martenstic structure and a high cold hardness. Adding alloying elements like chromium, molybdenum, tungsten and vanadium in small amounts ranging from 0.25-0.5% together with manganese of the order of 0.6% gives rise to high carbon low alloying steels that can withstand temperatures up to 300^{o}C. Cr, Mo, W and V form carbides to give better wear resistance and manganese confers hardenability. . It is however now virtually superseded by other materials used in engineering because it starts to temper at about 220^{o}C. This softening process continues as the temperature rises. As a result cutting using this material for tools is limited to speeds up to 0.15 m/s for machining mild steel with lots of coolant. High carbon steel or plain carbon steel tools are used in low-speed machining operations because lose their hardness above 300^{o}C and do not regain it even after cooling.

1.8.2 High Speed Steel

High speed steel (HSS) contains significant amounts of W, Mo, Co, V and Cr besides Fe and C. W, Mo, Co and Cr in the ferrite as a solid solution provide strengthening of the matrix beyond the tempering temperature, thus increasing hot hardness. Vanadium along with W, Mo and Cr improves hardness and wear resistance. Some of the most commonly used alloying elements are manganese, chromium, tungsten, vanadium, molybdenum, cobalt, and niobium. While each of these elements will add certain specific desirable characteristics, it can be generally state that they add deep hardening capability, high hot hardness, resistance to abrasive wear, and strength, to HSS. These characteristics allow relatively higher machining speeds and improved performance over plain high carbon steel.

Typical composition of 18-4-1 type (tungsten 18%, chromium 4%, and vanadium 1%). There are two basic types of HSS: molybdenum (M Series) and tungsten (T series). The M series contains up to about 10% molybdenum, with chromium, vanadium, tungsten and cobalt as alloying element. The T series contains 12-18% tungsten, with chromium, vanadium, vanadium, and cobalt as alloying elements. The M series generally has higher abrasion than T series, undergoes less distortion during heat treating, and is less expensive.

1.8.3 Cast Cobalt Alloys (Stellite)

Developed independently to H.S.S., Cast Cobalt Alloys do not use Steel; typically they are composed of 38 to 53% Cobalt, 30 to 33% Chromium and 10 to 20% Tungsten. Cast Cobalt Alloys or Stellite tools have good hardness (58 to 64 HRC) but are not as tough as H.S.S. They are suitable for rapid stock removal at elevated temperatures and cutting speeds but are sensitive to impact and shock.

1.8.4 Cemented Carbide Tool

The two groups of tool materials described previously have sufficient toughness, impact strength, and thermal shock resistance, but have important limitations on characteristics such as strength and hardness, particularly hot hardness. Consequently, they cannot be used as effectively where high cutting speeds, and hence high temperatures, are involved; thus, their tool life can be short. To meet the challenge of higher speed for higher production rates, carbides (also known as cemented or sintered carbides) were introduced in the 1930s. Because of their high hardness over a wide range of temperatures, high elastic modulus and thermal conductivity, and low thermal expansion, carbides are among the most important, versatile, and cost-effective tool and die materials for a wide range of applications. However, stiffness of the machine tool is important and light feeds, low cutting speeds, and chatter can be detrimental. The two basic groups of carbides used for machining operations are tungsten carbide and titanium carbide. In order to differentiate them from coated tools, plain carbide tools are usually referred to as uncoated carbides.

a) Tungsten Carbide: Tungsten carbide (WC) is a composite material consisting of tungsten-carbide particles bonded together in a cobalt matrix; hence, it is called cemented carbide. Tungsten-carbide tools are manufactured by powder-metallurgy techniques in which WC particles are combined together with cobalt in a mixer, resulting in a cobalt matrix surrounding the WC particles. These particles, which are 1-5µm in size, are then pressed and sintered (hence tungsten carbide is also called sintered carbide) into the desired insert shapes.

WC is frequently compounded with carbides of titanium and niobium to impart special properties to the carbide.

The amount of cobalt significantly affects the properties of carbide tools. As the cobalt content increases, the strength, the hardness and wear resistance decrease, while the toughness increases, because of the higher toughness of cobalt. Tungsten-carbide tools are generally used for cutting steels, cast irons, and abrasive nonferrous materials and have largely replaced HSS tools in many applications, due to the better performance of the tungsten-carbide tools.

b) Titanium Carbide: Titanium carbide (TiC) has higher wear resistance than that of tungsten carbide, but is not as tough. With a nickel-molybdenum alloy as the matrix, TiC is suitable for machining hard materials, mainly steels and cast irons, and for cutting at speeds higher than those for which tungsten carbide may be used.

1.8.5 Ceramic (Cemented oxides)

It appears that the word 'Ceramics' is derived from the fact that the materials are made by sintering at extremely high temperature approaching to that of pottery ceramics. Amongst the numerous ceramic tool materials available (Aluminum oxide, Silicon carbide, Boron carbide, Titanium Carbide, Titanium boride), the best results have been obtained with alumina (or Aluminum oxide) or Aluminum oxide 90% combined with other oxides (Cr_2O_3, MgO & NiO).

Ceramics are very hard & have a high degree of compressive strength (30000-35000 kg/cm^2 even at elevated temperatures. They have good abrasive wear resistance, low coefficient of friction & can retain cutting edge hardness up to about 7600^{o}C (& exhibit uniform strength up to 6000^{o}C) permitting higher cutting speed (800 m/min). They have low transverse rupture strength (1/2 to 1/3 of that of carbides) restricting their applications in interrupted cuts only. But through better raw materials, composition modifications & closer control over process variables can be used in interrupted cuts of light to medium severity on cast iron & steel work pieces. Ceramics have poor weldability and hence permit their use on high abrasive and reactive materials at higher cutting speeds. But due to poor weldability brazing of tip with steel shank is not possible. This problem can be solved by epoxy resin cementing of ceramic tools to steel shanks. Low thermal conductivity produces some problem of thermal shock due to rise of thermal gradient but is not of that severity. Cermets are acid resistant, non-magnetic, non-conducting & non-corrosive. They have more flexibility of machining i.e. wide range of materials can be machined at various speeds ranging from 200 rpm to 800 rpm.

1.8.6 Diamond Tools

Diamond; because of its high modulus of elasticity, chemical inertness & exceptionally high hardness is ideal for obtaining fine surface finish & accuracy. Though initial cost of the tools is high, the cost per piece is less due to very high tool life. It can be used as cutting tool material, in the form of either a single crystal or a polycrystalline compact. The single crystal diamond may be natural or synthetic. It has both hard & soft axes. If the diamond is used in the direction of soft axis (or parallel to cleavage plane) it wears out quickly. Polycrystalline diamond is produced by sintering very fine powder of diamond at high temperature or pressure. Sometimes polycrystalline diamond compacts are brazed to each corner of carbide insert. Because of random orientation of diamond particles in diamond compact, any direction can be used for cutting (as there are no hard or soft axes).

1.9 Performance of Coated Tool Materials

Coatings are applied on tool materials to improve the surface strength and/or reduce the chip-tool interface friction. Developments in cutting tools and machine tools in the last few decades have made it possible to cut materials in their hardened state. The advantages of producing components in hardened state can be reduction of machining costs, reduction of lead time, reduction of number of necessary machine tools, improved surface integrity, reduction of finishing operations and elimination of part distortion caused by heat treatment.

The development of coating techniques, particularly chemical vapor deposition (CVD) and physical vapor deposition (PVD) on high speed steel and cemented carbide tools has reached a top level in the beginning of the 1980s with the advent of TiN coated tools. Since then, research in this field has expanded considerably and has caught the attention of researchers. The outstanding performance of TiN coatings, together with the evolution of the deposition techniques, has allowed the development of single layer to multilayer coatings.

Fig. 1.10: CVD Coating on substrate

The CVD-coating process dominates for indexable inserts providing excellent heat, chemical and abrasive wear barriers for the insert. New developments in relieving stress in the coating have improved performance as have gradient technology, where the insert substrate is provided with hardness and toughness where it is most needed. This photo shows a steel turning grade with a thick, alumina coating on top of a titanium carbonitride layer, with good adherence to a gradient-substrate.

Fig. 1.11: PVD Coating on substrate

PVD-coatings are on the increase. There is a growing need for these thinner coatings, more suitable for positive, sharper tools. Smaller machine tools need tools that cut with lower power consumption and are more forgiving when it comes to instability, intermittent cuts and unfavorable tool entries and exits. This photo shows a thin PVD-coating on a positive indexable insert for an endmill.

Typical coating material includes TiN, TiC, TiCN, Al_2O_3, TiAlN, TiZrN, TiB_2 and recently introduced diamond coatings. It is estimated that 40% of all cutting tools used in the industry are coated and 80% of them are used for machining purpose. Generally in the thickness range of 2-10 µm, these coatings are applied on tools and inserts by chemical vapor deposition (CVD) and physical vapor deposition (PVD) on cemented carbide tools. The CVD process is the most commonly used coating application method for carbide tools with multiphase and ceramic coatings. The PVD coated carbides with TiN coatings, on the other hand, have higher cutting-edge strength, lower friction, lower tendency to form a built-up edge, and are smother and more uniform in thickness, which is generally in the range of 2-4 µm. a more recent technology, particularly for multiphase coating is medium-temperature chemical vapor deposition (MTCVD); it provides a higher resistance to crack propagation than CVD coatings.

The coatings should have the following general characteristics:

- High hardness at elevated temperatures
- Chemical stability and inertness to the workpiece material
- Low thermal conductivity
- Good bonding to the substrate to prevent flanking or spalling
- Little or no porosity

The effectiveness of coatings, in turning is enhanced by hardness, toughness, and high thermal conductivity of the substrate, which may be carbide or HSS.

The basic insert – the substrate provides most of the required toughness for the cutting tool, while the coating adds wear protection and increases the hardness. Coating provides a good abrasion resistance and acts as a thermal and chemical barrier between the tool and workpiece and increases the tool life. They have excellent high temperature properties such as high resistance to diffusion wear, superior oxidation wear resistance and high hot hardness. The good lubricating properties of the coatings minimize friction at the tool-chip and tool-workpiece interfaces, thus lowering cutting temperature. Coating materials also lowers forces generated during machining relative to uncoated tools. A better chip control and reduced adherence of workpiece material (BUE formation) onto the cutting tool provides the better surface finish on the machined component.

Coated inserts reduce the frequency of tool indexing or changing and give savings in down time and cost. With the expensive machine tools in use today, this has a big effect in reducing production costs. Simply stated, coating reduces the cost and increases the efficiency.

a) **Titanium Nitride (TiN):** TiN coatings have a low coefficient of friction, high hardness and high resistance to high temperature and good adhesion to the substrate. Consequently they greatly improve the carbide tools. TiN coated tools perform well at higher cutting speeds and feeds. Flank wear is significantly lower than for uncoated tools flank surfaces can be reground after use; regrinding does not remove the coating on the rake face of the tool.
b) **Ceramic Coatings:** Because of their resistance to high temperature, chemical inertness, low thermal conductivity, resistance to flank and crater wear, ceramics are

suitable coatings for tools. The most commonly used ceramic coating is aluminum oxide (Al_2O_3).

c) **Titanium Carbide:** Titanium carbide (TiC) coatings on tungsten carbide inserts have high resistance to flank wear in machining abrasive materials.

d) **Titanium Carbonitride:** Titanium carbonitride (TiCN), which is deposited by PVD techniques, is harder and tougher than TiN. It can be used on carbides and HSS tool and particularly effective in cutting stainless steels.

e) **Multiphase Coatings:** The desirable properties of the type of coating just described can be combined and optimized with the use of multiphase coatings. Carbide tools are available with two or three layers of such coatings and are particularly effective in machining cast iron and steels.

The first layer over the substrate is TiN, followed by TiCN, and then again TiN. The first layer should bond well with the substrate; the outer layer should resist wear and have low thermal conductivity; the intermediate layer should bond well and be compatible with both layers. Typical applications of multiphase coating tools are:

- High speed continuous cutting: TiC/Al_2O_3
- Heavy duty continuous cutting: $TiC/TiN/Al_2O_3$
- Light interrupted cutting: TiC/TiC + TiN/TiN

1.10 Taguchi Method

The Taguchi experimental design method is a well-known, unique and powerful technique for product or process quality improvement [8]. It is widely used for analysis of experiment and product or process optimization. Taguchi has developed a methodology for the application of factorial design experiments that has taken the design of experiments from the exclusive world of the statistician and brought it more fully into the world of manufacturing. His contributions have also made the practitioner’s work simpler by advocating the use of fewer experimental designs, and providing a clearer understanding of the nature of variation and the economic consequences of quality engineering in the world of manufacturing. Taguchi introduces his concepts to:

- Quality should be designed into a product and not inspected into it.
- Quality is best achieved by minimizing the deviation from a target.

- The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

Taguchi recommends a three-stage process to achieve desirable product quality by design- system design, parameter design and tolerance design. While system design helps to identify working levels of the design parameters, parameter design seeks to determine parameter levels that provide the best performance of the product or process under study. The optimum condition is selected so that the influence of uncontrollable factors causes minimum variation to system performance. Orthogonal arrays, variance and signal to noise analysis are the essential tools of parameter design. Tolerance design is a step to fine-tune the results of parameter design [9].

1.11 Regression Analysis

In its simplest form regression analysis involves finding the best straight line relationship to explain how the variation in an outcome (or dependent) variable, Y, depends on the variation in a predictor (or independent or explanatory) variable, X. Once the relationship has been estimated we will be able to use the equation:

$$Y = b_0 + b_1 X$$

In order to predict the value of the outcome variable for different values of the explanatory variable multiple regression is a statistical technique that allows us to predict someone's score on one variable on the basis of their scores on several other variables. Of course this is only useful if most of the variation in the outcome variable is explained by the variation in the explanatory variable. In many situations the outcome will depend on more than one explanatory variable. This leads to multiple regressions, in which the dependent variable is predicted by a linear combination of the possible explanatory variables.

When using multiple regression in psychology, many researchers use the term "independent variables" to identify those variables that they think will influence some other "dependent variable". We prefer to use the term "predictor variables" for those variables that may be useful in predicting the scores on another variable that we call the "criterion variable". Human behavior is inherently noisy and therefore it is not possible to produce totally accurate predictions, but multiple regression allows us to identify a set of predictor variables which together provide a useful estimate of a participant's likely score on a criterion variable.

1.12 Optimization Methodology Implemented in Present Study

Taguchi approach is a well-known statistical method to optimize the input parameters to get best output results within a less time and cost. But one drawback of the Taguchi method is that, we can optimize the input parameters for only one output response at a time. That's why Taguchi approach is not suitable for multi objective optimization problems. So, to optimize the input parameters for multi objective output responses in Taguchi approach, first we have to convert the multi responses into a single equivalent response. There are number of techniques available to convert multi responses into a single response. In the present study, three different multi objective optimization techinques have been employed to determine optimal settings of input parameters.

1.12.1 Grey Relational Approach

In Grey relational analysis, black systems refer to those systems for which no information is available, white systems refer to those systems for which all the information correlating the data and the responses are present and grey systems refer to those systems for which some information is known in advance. Grey system level lies in between that of black and white system levels (Fig. 1.12). Grey relational analysis finds its usefulness in multi response problems in which single objective optimization techniques cannot be applied.

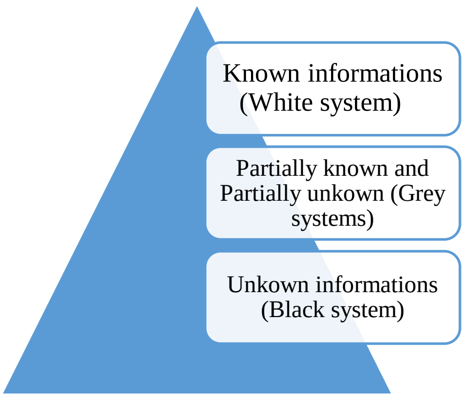


Fig. 1.12: Pyramid view of grey relational approach

Following procedure has been adopted for optimizing multi response systems using GRA technique:

a)Data pre-processing (Normalizing the output responses)

In this step, all the output responses to be optimize (either minimize or maximize) have to be normalized in the range of 0 and 1. Those output responses which need to be maximized have to be normalized using 'higher the better characteristic' and the output responses which need to be minimized have to be normalized by applying 'lower the better characteristic'. In present research, different output parameters machining forces, temperature and flank wear were of 'lower the better' characteristic and hence have to be minimized. Thus, the following equation has been used to normalize the above stated output responses:

$$X_i^*(k) = \frac{\max yi(k) - yi(k)}{\max yi(k) - \min yi(k)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where, i = 1,2…m; k= 1,2..n; m is the total number of experimental runs and n is the number of output responses; $\min y_i(k)$ and $\max y_i(k)$ are the minimum and maximum values of the output response under consideration. X_i^* (k) is the obtained normalized value.

b) Grey relational coefficient calculation

After normalizing the data, grey relational coefficient has been evaluated which represents the correlation between the optimal and normalized sequences. The grey relational coefficient can be calculated by using the following formulae:

$$\xi_i(k) = \frac{\Delta_{\min} + \tau\Delta_{\max}}{\Delta_{0i}(p) + \tau\Delta_{\max}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

Where, ξ_i (k) represents the grey relational coefficient, τ is the identification coefficient (or distinguishing factor) which varies from 0 to 1 but it is generally taken as 0.5. For the sensitivity checking one can examine all the values of τ between zero to one. $\Delta_{\min}$ and $\Delta_{\max}$ are the minimum and maximum quality loss values of the normalized sequence.

c) Grey relational grade calculation

Grey relational grade represents the degree of influence that the normalized sequence exerts over the original sequence. A higher value of grey relational grade represents a relatively higher degree of influence exerted on the original sequence by the comparative sequence and vice versa. Grey relational grade is mathematically evaluated as the weighted sum of the grey relational coefficients as shown below:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\zeta_i(k) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

γ_i represents the grey relational grade for the corresponding sequence. In GRA, the weighted sum of the grey relational coefficients is approximated to the average value of the coefficients. The distribution of weightage to the output responses may vary according to the importance of any particular output response during the calculation and can be assigned judiciously by the operator. The sum of the weightage should not exceed 1. Since, higher grey relational grade represents the most influential sequence order, therefore that combination of process parameters is expected to yield best result. Hence, the Signal-to-Noise ratio of the corresponding highest grey relational grade can be considered as the optimal combination of process parameters.

CHAPTER 2

LITERATURE REVIEW

According to Pal et al. [10] machining of work piece material having hardness up-to 45 HRC is treated as soft machining. On the other hand, machining of work piece having hardness in the range of 45-70 HRC is considered under hard machining. They have done turning operations on AISI 4340 steels of hardness values 35, 45, 55 HRC with the help of mixed alumina ceramic tools. Harder work piece resulted in higher cutting forces, higher tool-chip interface temperature but lower surface roughness. Surface roughness was more prominently affected by feed rates whereas radial forces by the depth of cut. Cutting speed and depth of cut were more significant when it came to average chip-tool interface temperature. This finding is in line as per the experiments done by Chinchanikar and Choudhury [11] on AISI 4340 steel with single-layer TiAlN coated (PVD) and multi-layer TiCN/ Al_2O_3/ TiN coated (CVD) carbide tools. They have seen the chip-tool interface temperature to increase rapidly with cutting speed, slightly with feed but to remain almost same with the depth of cut. Moreover, the temperature was found to be greater in case of CVD coated tools than PVD coated ones. They have also developed a mathematical model to predict chip-tool interface temperature which was valid over a wide range of cutting conditions. D'Errico et al. [12] used uncoated and TiN, Ti(C,N) coated cermet inserts with and without chamfered edge in continuous and interrupted turning operation of SAE 1045 steel. From the experimental results they concluded that PVD coated inserts without chamfered edge performed well only in continuous turning rather than interrupted turning. Furthermore, they stated that tools with chamfered edge are better for interrupted turning where the high depth of cut is involved. There was no significant effect of coating on tool life irrespective of their cutting edges in interrupted turning. Khan and Hajjaj [13] worked on the capabilities of TiN coated cermet tools on high speed machining of austenitic stainless steel. SEM images discovered that the failure of cutting edges of cermet tools started with micro-cracks which grew gradually to cause the tool failure due to low fracture toughness. It gave satisfactory results to use cermet tools while machining at low speed, feed and depth of cut because of good surface finish and long tool life. The authors recommended to keep the cutting speed under 300 m/min, feed rate under 0.2 mm/rev and depth of cut under 0.3 mm to have a satisfactory tool life. The similar point of view was shared by Noordin et al. [6] who found the tool life of TiCN based cermet inserts to be highest at low cutting speed and feed rate. However, the performance of coated carbides was superior at medium and high cutting speed and feed. Also, from the experimental results, they observed that with an increase in negative side cutting edge angle, tool life increased. But, Adesta et al. [14] showed there is a decrease in tool life and surface finish with increasing negative rake angle. This was due to increase in cutting force and excessive heat generation. Tool life was also dependent on the speed of cutting. At high speed, tool life was shorter but at the same time, the surface finish was found out to be finer. Ghani et al. [15] investigated on the wear mechanisms in the end milling operation of AISI H13 tool steel using TiN coated carbide and uncoated cermet inserts. They assessed that the flank wear at the flank face predominantly controlled the tool wear phenomenon. Besides, they observed that the time taken by coated carbides to initiate cracking and fracturing is more than that of uncoated cermet. They also concluded with low cutting parameters, uncoated cermets experience more uniform and gradual wear compared to coated carbides. Suresh et al. [16] analyzed the effect of various process parameters on the machinability aspects in hard turning of AISI 4340 steel with multilayer coated carbide inserts. Experiments revealed that tool wear and machining power were mostly influenced by cutting speed and tool wear was commonly due to abrasion. Whereas, for machining force, specific cutting force and surface roughness, feed rate is the most significant parameter which was congruent with the assessment made by Selvaraj et al. [17] who optimized surface roughness, cutting force and tool wear of nitrogen alloyed duplex stainless steel in a dry turning process using coated carbide inserts. They also resolved that cutting speed was the most significant parameter in tool wear. The tool wear was due to abrasion at lower cutting speeds and due to diffusion, thermal softening and notching at higher cutting speeds. Ozkan et al. [18] did a comparative analysis for the performance of coated carbide and cermet cutting tools in turning of 50CrV4 steel. The minimum and maximum values of surface roughness were obtained with cermet and carbide inserts respectively. Also, they observed that coated carbide tools resulted in maximum axial, radial and cutting forces whereas respective minimum values were attained with cermet inserts. Thoors et al. [19] performed dry turning operation on two variants of quenched and tempered steel and one ball bearing steel with the help of cermet and tungsten-carbide based inserts. Cermet tools were found to have low friction and wear resistance compared to carbide tools. Moreover, tool-chip contact stresses were different on the basis of the types of work piece materials. Prevalent mechanisms of crater and flank wears in cermet tools were abrasion and adhesive damage in machining of quenched and tempered steel, while plastic deformation and cracking and occasional micro-chipping in case of bearing steel. But, Sahoo and Sahoo [20] stated that abrasion and chipping were main mechanisms of wear in the hard turning of AISI 4340 steel using indexable multi-layer coated carbide inserts. The surface finish was within recommendable range when using carbide inserts compared to cylindrical grinding. As well as, the colour transformation of chips from metallic to burnt blue was much delayed using TiN coated carbide inserts which meant a more favourable machining. From the machinability study, it was evident that thrust force was the largest component followed by tangential and feed force. Reduction in cutting forces at higher cutting speed was also observed. Speed and feed were the most notable parameters for tool life and surface quality. Sert et al. [21] studied wear behaviour of PVD TiAlN, CVD TiN coated carbides and uncoated cermet cutting tools in turning of AISI 5140 steel. Tool wear rate had a great effect on surface roughness and dimensional deviation. Based on experimental observations, they discouraged the use of uncoated cermet tools in machining of AISI 5140 steel at high speed because of high wear rate. They illustrated that TiN coated inserts fared better than TiAlN coated inserts at higher speed range. Fnides et al. [22] evaluated the tool lives of various cutting materials, viz. carbides (H13A and GC3015), ceramics (mixed CC650 and reinforced CC670) and cermet (uncoated CT5015 and coated GC1525) in dry turning of AISI H11 steel, treated at 50 HRC and it was mostly affected by speed. The tool lives of uncoated and coated cermet inserts were found out to be the minimum, which were less than 2 minutes; whereas maximum tool life was obtained with mixed ceramic, which was 49 minutes. Quazi et al. [23] optimized cutting parameters in turning operation of mild steel, EN-8 and EN-31 steel using cermet inserts with grades of TN60, TP0500 and TT8020 for surface roughness and in this process, used Taguchi's L_9 Orthogonal Array for the design of experiment. From the results, they inferred that the minimum surface roughness values for mild steel and EN-8 steel were acquired using TN60 and for EN-31 steel with TT8020 tools. Pawade and Joshi [24] had proposed to study the optimization of high speed turning process parameters by selecting the force and surface roughness as output response, and found that the feed rate was the dominating factor for both outputs. The surface alteration was mostly affected by lower cutting speed as well. Sait et al. [25] employed Taguchi's L18 orthogonal array to determine the optimal settings of input parameters and found that moderate cutting speed, lower feed and higher depth of cut are the best machining combinations for machining hand layup GFRP pipes and moderate cutting velocity, feed rate and lower depth of cut are the ideal machining parameters for machining filament wound GFRP pipes. Mishra and Gangele [26] suggested that Taguchi method and utility concept can be used to determine the optimal settings of the process parameters for a multi quality characteristics like flank wear, surface roughness and roundness while machining AISI 1045 steel bars. They have recommended the optimal setting for output responses were - speed = 110 m/min., feed rate = 0.15 mm/rev., and depth of cut = 0.20 mm. Nayak et al. [27] and Lin [28] used Grey-relational analysis for the purpose of multi-objective optimization of performance characteristics in turning operation. Datta and Mahapatra [29] did Principle Component Analysis of correlated surface quality characteristics of Mild Steel turned product.

2.1 Motivation

It has been reflected from the literature studies that there was a lack of usage of coated cermet inserts in machining of AISI 4340 alloy steel, however in this regard extensive use of carbide inserts has been found, among which some of the works were done on AISI 4340 steel of hardness above 45 HRC. Also comparative analyses between the aforementioned inserts were observed only in case of stainless tool steels, alloy and ball bearing steels, but not in this specific alloy steel (AISI4340) at 48HRC. Furthermore, the researchers have not studied workpiece surface temperature as an output response.

2.2 Objective

In view of the above mentioned research gap, the objective of our research is based on comparative analysis of uncoated carbides and multilayer coated cermets in hard turning of AISI 4340 alloy steel which was hardened to 48 HRC. The machining operation was done in dry circumstances according to Taguchi's L_9 standard orthogonal array. The machinability aspects of the workpiece have been investigated based on output responses like flank wear, workpiece surface temperature and machining forces. Analysis of variance (ANOVA) was conducted to identify which of the input parameters were significant in affecting the specified responses. These responses were fitted in the regression models with respect to the input variables and their interactions. Also, the various output responses were optimized using multi-response methodology like Grey Relational Analysis.

CHAPTER 3

EXPERIMENTAL DETAILS

Fig. 3.1 shows the cylindrical bar of 50 mm diameter and 700 mm length made of AISI 4340 alloy steel which is used for the experiment.

Fig. 3.1: Workpiece

Three parameters such as speed, feed and depth of cut have been varied at three levels during hard turning and their influences on output responses like flank wear, workpiece surface temperature and forces have been examined. The experimental runs have been designed according to Taguchi's L_9 orthogonal array so as to save both time and cost as compared to full factorial design without notably compromising the accuracy of results. Before starting actual machining operation, the rough layers were first removed from the outer surface of the specimen to mitigate any consequences of non-uniformity on the output responses. Machining length was fixed at 300 mm for each experimental run. Readings of cutting, feed and radial forces have been recorded in each experimental run. Workpiece surface temperature was measured in three divisions i.e. 0 – 100 mm, 100 - 200 mm and 200 – 300 mm of cutting length and their mean has been evaluated. A particular cutting edge of inserts was used for entire machining length in an experimental run. After each such trial, the flank wear of the insert was observed.

3.1 Test sample

AISI 4340 alloy steel is tough to machine because of excessive hardness, low specific heat and its likelihood for strain hardening. It is a low alloy steel comprising nickel, chromium and molybdenum which can be heat treated. The toughness of the material is high and also attains high strength after heat treatment, at the same time maintaining good fatigue strength. This steel can undergo all conventional machining processes. To obtain best results during machining, it is advisable to anneal or normalize and temper the material. This particular alloy steel is very popular in the automobile industry in the making of various parts like gears, bearings, axles, shafts etc. It can also be used as a material for various structural and aircraft components. Table 3.1 shows the chemical composition of the sample as found out using Spectrometal Analyzer.

Table 3.1: Chemical composition of specimen

Elements	Weight Percentage
Carbon	0.397
Silicon	0.339
Manganese	0.770
Nickel	1.550
Chromium	0.900
Molybdenum	0.275

3.2 Heat treatment

The workpiece is heated over 870 °C, i.e. upper critical temperature, where the solid solution of iron and carbon would exist. After austenization the workpiece was held at the same temperature for nearly thirty minutes, to execute the respective reformations in the crystalline structure, and quenched in oil. After quenching the tempering was accomplished by reheating the working substance to a predestined temperature at about 400℃, below the lower critical temperature for 2 hours. Then it was cooled in still air for taking away the residual stresses to acquire the homogeneous structure. After heat treatment, hardness of the sample got increased from 18 HRC to 48 HRC as measured on Rockwell hardness testing machine with an indentation of 105 kgf load by the sphero-conical diamond indenter.

3.3 Cutting Tools

In the present work, two types of cutting inserts have been used, uncoated carbides and multilayer PVD coated cermets. Uncoated carbides are Tungsten, Cobalt based, designated by SNMG 120408 of grade K313 from Kennametal. The shape of the inserts was square (90º point angle) without any specific chip breaker geometry which was mounted on tool holder of ISO designation PSBNR 2020K12 as shown in Fig. 3.2. The tool holder has the following cutting geometries i.e. clearance angle = 0º, back and side rake angle = -6º, entering angle = 75º, point angle = 90º and nose radius = 0.8 mm.

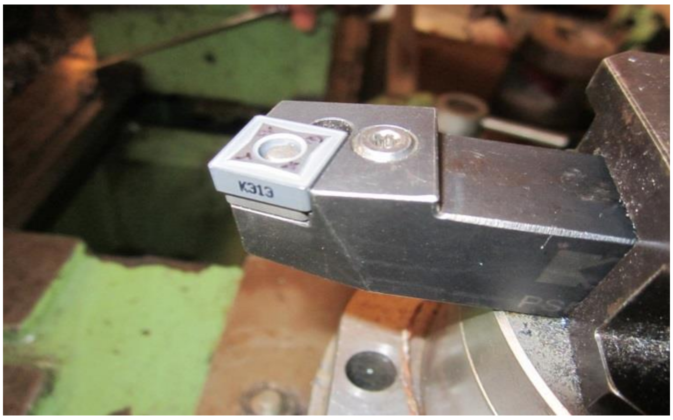


Fig. 3.2: Uncoated carbide with designated tool holder

Constituents of cermet are ceramic particles with metallic binders. Cermet inserts used in this experiment were multilayer (TiN/TiCN/TiN) PVD coated of designation CNMG 120408 defined by grade KT315ff from Kennametal of rhombic shape (80º point angle) with the presence of fine finish chip breaker geometry as shown in Fig. 3.3.

Fig. 3.3: Cermet insert

Fig. 3.4 shows the tool holder used in this work which belongs to ISO designation PCLNR 2020K12 with clearance angle = 0º,back and side rake angle = -6º,entering angle = 95º, point angle = 80º and nose radius = 0.8 mm.

Fig. 3.4: Tool holder for cermets

For both the inserts nose radius and back rake angle were same (0.8 mm, -5º). Titanium nitride coatings were given at inner and outer most layers, and Titanium carbonitride as an intermediate layer. The designations of the inserts are explained in Table 3.2.

Table 3.2: Nomenclature of inserts

S	Insert shape (90º square)
C	Insert shape (80º rhombic)
N	Clearance angle (0º)
M	Tolerance class [± 0.002 for inscribe circle (d), ± 0.003 for height of insert (m), ± 0.0005 for thickness (s)]
G	Insert features – no of cutting edges with types of chip breaker geometry
12	Cutting edge length (12 mm)
04	Insert thickness (4.76 mm)
08	Nose radius (0.8 mm)

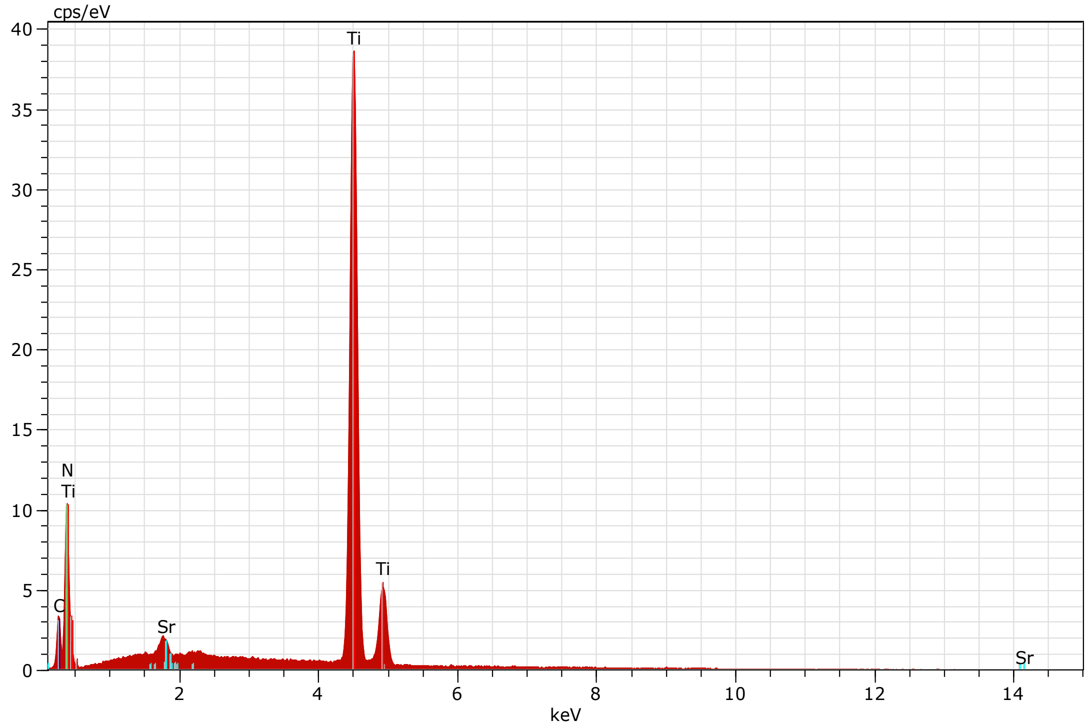


Fig. 3.5: EDAX analysis of coated cermet

Fig. 3.5 shows the EDAX analysis of the coated cermet insert and the percentage of elements found from it are shown in Table 3.3.

Table 3.3: Percentage of elements in coated cermet

Element	Normalized C (wt %)	Atomic C (at %)
Ti	77.91	51.17
N	15.14	34.00
C	5.46	14.30
Sr	1.49	0.54

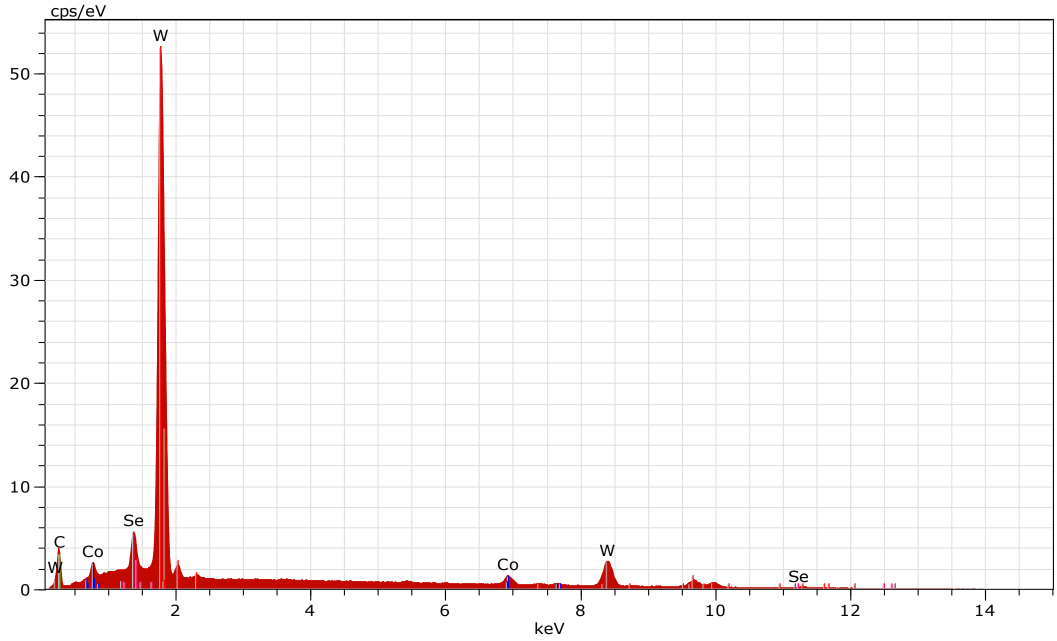


Fig. 3.6: EDAX analysis of uncoated carbide

Fig. 3.6 shows the EDAX analysis of the uncoated carbide insert and the percentage of elements deduced from it are shown in Table 3.4.

Table 3.4: Percentage of elements in uncoated carbide

Element	Normalized C (wt %)	Atomic C (at %)
W	83.07	30.06
C	11.52	63.84
Co	5.40	6.10

3.4 Machine tool and measuring instruments

Fig. 3.7 shows the experimental set up. The turning operations were executed on a heavy duty lathe of HMT make with spindle power of 11 kW and of speed range 40 to 2040 rpm. For measurement of cutting forces Kistler three dimensional dynamometer was used and the temperature was measured using an infrared thermometer. Flank wear of the inserts were analyzed using advanced optical microscope of model 100HD-3D (Carl Zeiss) and scanning electron microscope (JEOL JSM-6084 LV).Elemental analyses of both the inserts were done with the help of a Nova Nano Field Emission Scanning Electron Microscope.

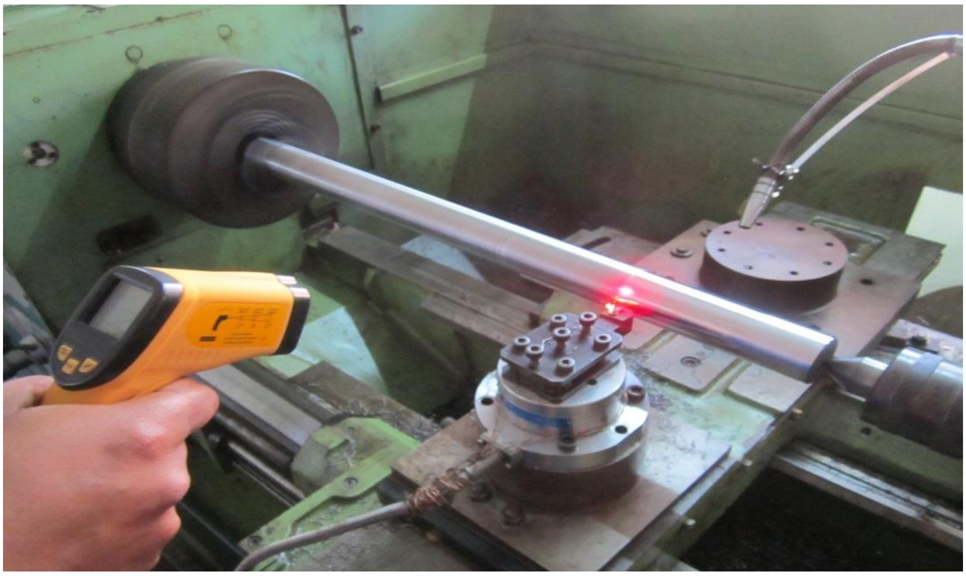


Fig. 3.7: Experimental setup with force and temperature measurement

3.5 Cutting Conditions

Various machining conditions adopted during the experiment are shown in Table 3.5.

Table 3.5: State of machining

Machining Conditions	Descriptions
Workpiece Material	AISI4340
Hardness	48 HRC
Spindle Speed	500, 600, 700 rpm
Feed	0.05, 0.1, 0.15 mm/ rev
Depth of cut	0.1, 0.2, 0.3 mm
Cutting environment	Dry
Cutting inserts	Tool 1: Uncoated carbide (K313) Tool 2: Multilayer coated cermet (KT315)
Tool geometry	SNMG 120408, CNMG120408
Tool holder	PSBNR 2020K12, PCLNR 2020K12
Machining length	300 mm
Output responses	Flank wear; Feed, Cutting and Radial forces; Workpiece surface temperature.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results of the experiment

4.1.1 Uncoated carbides

For each of the nine experimental runs, the responses like three machining forces F_x, F_y and F_z flank wear of the insert VBc and workpiece surface temperature T are measured as shown in Table 4.1. The three cutting parameters namely spindle speed; feed and depth of cut for each experiment are also mentioned in this table.

Table 4.1: Responses for uncoated carbide

Experimental run	**Spindle speed (rpm)**	**Feed (mm/rev)**	**Depth of cut (mm)**	**F_z(N)**	**F_x(N)**	**F_y(N)**	**VBc (mm)**	**T (°C)**
1	500	0.05	0.1	103	70	245	0.33000	27
2	500	0.10	0.2	270	165	490	0.52000	25
3	500	0.15	0.3	260	222	505	0.34710	38
4	600	0.05	0.2	224	121	280	0.80000	49
5	600	0.10	0.3	232	203	382	0.72000	56
6	600	0.15	0.1	90	72	236	0.32780	52
7	700	0.05	0.3	205	181	262	0.93830	60
8	700	0.10	0.1	85	78	211	0.77003	53
9	700	0.15	0.2	230	143	359	0.65000	50

4.1.2 Coated cermets

The abbreviations used for the previous table are also used with coated cermet inserts and the experimental results are tabulated below in Table 4.2.

Table 4.2: Responses for coated cermet

Experimental run	Spindle speed (rpm)	Feed (mm/rev)	Depth of cut (mm)	F_z(N)	F_x(N)	F_y(N)	VBc (mm)	T (°C)
1	500	0.05	0.1	97	133	433	0.19140	28
2	500	0.10	0.2	111	159	558	0.13110	27
3	500	0.15	0.3	150	197	632	0.11020	32
4	600	0.05	0.2	72	168	641	0.14110	36
5	600	0.10	0.3	98	196	705	0.05360	39
6	600	0.15	0.1	50	163	696	0.08170	26
7	700	0.05	0.3	111	192	708	0.17099	57
8	700	0.10	0.1	68	159	677	0.11300	42
9	700	0.15	0.2	86	189	758	0.14000	44

4.2 Analysis of variance (ANOVA)

Analysis of variance is used to observe the significance of controlling parameters on outcomes of the experiments. The results of ANOVA carried out at 95% confidence level have been shown in Tables 4.3 for various combination of cutting tools (i.e. uncoated carbide, coated cermet) and output responses (i.e. cutting force, feed force, radial force, flank wear and workpiece surface temperature). For each combination, the significance of three cutting parameters such as spindle speed, feed and depth of cut have been examined.

Table 4.3: ANOVA of cutting force with uncoated carbide at significance level of 5%

Source	DF	SS	MS	F	P	Remarks
Speed	2	2334.9	1167.4	656.69	0.002	Significant
Feed	2	597.6	298.8	168.06	0.006	Significant
Depth of cut	2	41689.6	20844.8	11725.19	0.000	Significant
Residual error	2	3.6	1.8			
Total	8	44625.6				

Table 4.4: ANOVA of feed force with uncoated carbide at significance level of 5%

Source	DF	SS	MS	F	P	Remarks
Speed	2	753.6	376.8	178.47	0.006	Significant
Feed	2	1086.9	543.4	257.42	0.004	Significant
Depth of cut	2	24889.6	12444.8	5894.89	0.000	Significant
Residual error	2	4.2	2.1			
Total	8	26734.2				

Table 4.5: ANOVA of radial force with uncoated carbide at significance level of 5%

Source	DF	SS	MS	F	P	Remarks
Speed	2	31976.0	15988.0	1713.00	0.001	Significant
Feed	2	20652.7	10326.3	1106.39	0.001	Significant
Depth of cut	2	44468.7	22234.3	2382.25	0.000	Significant
Residual error	2	18.7	9.3			
Total	8	97116.0				

Table 4.6: ANOVA of cutting force with coated cermet at significance level of 5%

Source	DF	SS	MS	F	P	Remarks
Speed	2	3302.00	1651.00	61.15	0.016	Significant
Feed	2	14.00	7.00	0.26	0.794	Not significant
Depth of cut	2	3528.00	1764.00	65.33	0.015	Significant
Residual error	2	54.00	27.00			
Total	8	6898.00				

Table 4.7: ANOVA of feed force with coated cermet at significance level of 5%

Source	DF	SS	MS	F	P	Remarks
Speed	2	468.22	234.11	27.72	0.035	Significant
Feed	2	533.56	266.78	31.59	0.031	Significant
Depth of cut	2	2820.22	1410.11	166.99	0.006	Significant
Residual error	2	16.89	8.44			
Total	8	3838.89				

Table 4.8: ANOVA of radial force with coated cermet at significance level of 5%

Source	DF	SS	MS	F	P	Remarks
Speed	2	44624.7	22312.3	199.22	0.005	Significant
Feed	2	12530.7	6265.3	55.94	0.018	Significant
Depth of cut	2	7340.7	3670.3	32.77	0.030	Significant
Residual error	2	224.0	112.0			
Total	8	64720.0				

Tables 4.3-4.5 reveal that all the three cutting parameters (i.e., speed, feed and depth of cut) are significant in affecting the cutting, feed and radial forces while machining with carbide tools, among which the depth of cut has the highest significance. Table 4.6 shows that speed and depth of cut are the significant factors for the cutting force in case of coated cermet. For the same coated cermet, Table 4.7 shows that feed force is affected by the depth of cut followed by feed and speed. Similarly, Table 4.8 indicates that all the three cutting parameters significantly affect the radial force in the decreasing order of speed, feed and depth of cut.

Table 4.9: ANOVA of flank wear with uncoated carbide at significance level of 5%

Source	**DF**	**SS**	**MS**	**F**	**P**	**Remarks**
Speed	2	0.225834	0.112917	28.34	0.034	Significant
Feed	2	0.113938	0.056969	14.30	0.065	Not significant
Depth of cut	2	0.069865	0.034933	8.77	0.102	Not significant
Residual error	2	0.007970	0.003985			
Total	8	0.417607				

Table 4.10: ANOVA of flank wear with coated cermet at significance level of 5%

Source	**DF**	**SS**	**MS**	**F**	**P**	**Remarks**
Speed	2	0.005143	0.002572	57.16	0.017	Significant
Feed	2	0.008107	0.004053	90.10	0.011	Significant
Depth of cut	2	0.001034	0.000517	11.49	0.080	Not significant
Residual error	2	0.000090	0.000045			
Total	8	0.014374				

It can be inferred from Table 4.9 that speed is the only dominant variable during experimenting with the flank wear of the uncoated carbides. Table 4.10 shows that feed is more effective than speed while considering flank wear of cermets.

Table 4.11: ANOVA of specimen temperature with uncoated carbide at significance level of 5%

Source	**DF**	**SS**	**MS**	**F**	**P**	**Remarks**
Speed	2	1094.89	547.444	133.16	0.007	Significant
Feed	2	6.22	3.111	0.76	0.569	Not significant
Depth of cut	2	160.89	80.444	19.57	0.049	Significant
Residual error	2	8.22	4.111			
Total	8	1270.22				

Table 4.12: ANOVA of specimen temperature with coated cermet at significance level of 5%

Source	**DF**	**SS**	**MS**	**F**	**P**	**Remarks**
Speed	2	566.222	283.111	2548.00	0.000	Significant
Feed	2	62.889	31.444	283.00	0.004	Significant
Depth of cut	2	176.222	88.111	793.00	0.001	Significant
Residual error	2	0.222	0.111			
Total	8	805.556				

It has been found from Table 4.11 that speed is also the most significant factor on workpiece temperature while cutting with uncoated carbide. Effect of depth of cut is important to a lesser extent. For cermet inserts, the input parameters can be ranked in the order of their prominence in workpiece surface temperature as speed, depth of cut, feed which can be seen in Table 4.12.

4.3 Mathematical modelling

The relationship between response and independent factors can be modelled as multiple linear regression when they are linearly related.

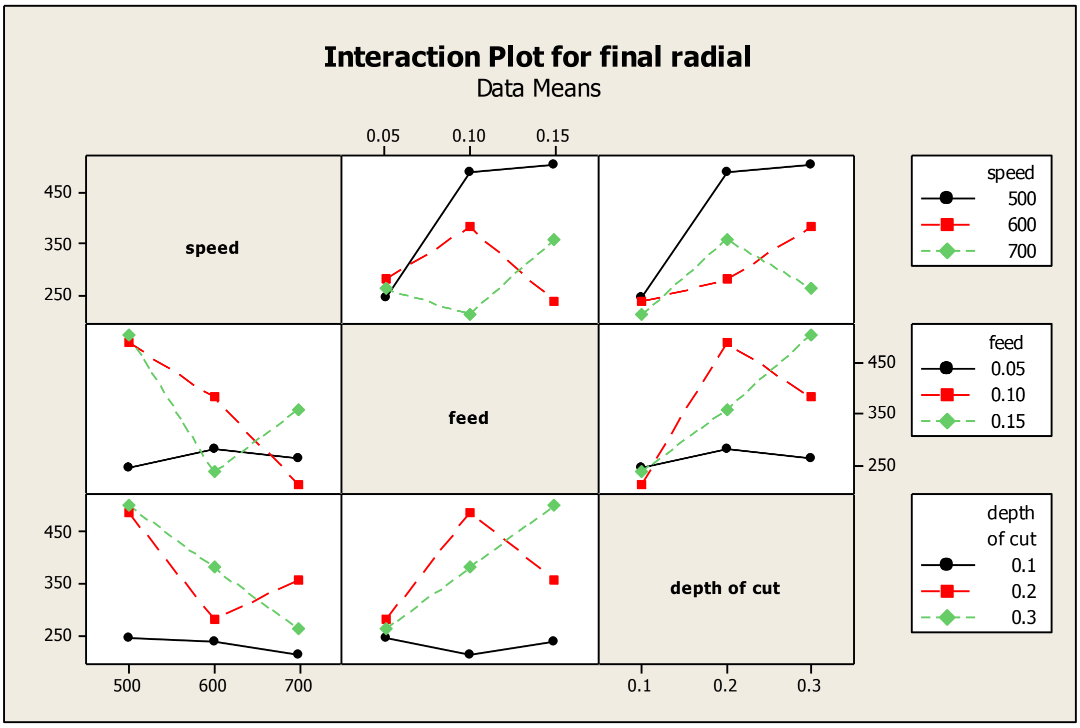


Fig. 4.1: Interaction plot for radial force using carbide inserts

On investigating the outcomes of the experiments with the help of interaction plots shown in Fig. 4.1, it has been found that all the interactions of machining parameters were viable in the results for both carbides and cermets. Hence, at the time of formulating the mathematical models, effect of interactions were reckoned. The multiple linear regression equations developed are given below.

For uncoated carbides:

F_z = 306.968 - 0.76619 N - 6728.57 f + 4803.33d + 13.4571 N*f - 4.88571 N*d - 8371.43 f*d ; R-Sq = 83.23% ……………………………………………………… (4)

F_x = 0.396825 - 0.0209524 N - 476.19 f + 1253.33 d + 1.08571 N*f - 0.928571 N*d-257.143 f*d ; R-Sq = 97.99% ……………………………………………………………… (5)

F_y = 495.905 - 0.885714 N - 5500.95 f + 4880.95 d + 11.7429 N*f - 5.5 N*d- 5257.14 f*d ; R-Sq = 86.86% ……………………………………………………………………... (6)

VBc = -1.37462 + 0.00267195 N - 13.3609 f + 15.079d + 0.0233134 N*f - 0.0184323 N*d

$- 24.742 f*d$; R-Sq = 98.70% ……………………………………………… (7)

$T = -78.254 + 0.168095 N + 341.905 f + 238.095 d - 0.285714 N*f - 0.2 N*d$

$- 885.714f*d$; R-Sq = 81.58% ………………………………………………………...… (8)

For coated cermets:

$F_z= 129.095 + 0.0857143 N + 1734.29 f - 1744.29d - 4.74286 N*f + 2 N*d + 6657.14 f*d$;
R-Sq = 90.18% ………………………………………………………………………….. (9)

$F_x = 44.0317 + 0.112857 N + 215.238 f + 286.667 d - 0.0571429 N*f - 0.114286 N*d - 28.5714 f*d$; R-Sq = 98.38% ……………………………………..………………(10)

$F_y = -98.1905 + 0.669524 N - 458.095 f + 3163.33d + 4.94286 N*f - 2.91429 N*d - 9428.57 f*d$; R-Sq = 96.57% ………………………...…………………...………….. (11)

$VBc = 0.508565 - 0.000186595 N + 2.0041 f - 4.78528 d - 0.00698486 N*f + 0.00571957N*d + 10.934 f*d$; R-Sq = 69.51%.. (12)

$T = -16.2698 + 0.119048 N + 303.81 f - 366.667 d - 0.914286 N*f + 0.471429 N*d + 1142.86 f*d$ R-Sq = 98.53% ……………………………………………………………… (13)

The parameter R squared (R-Sq) is used to judge the proximity of the responses with the fitted multiple regression line. R-Sq is named as the coefficient of multiple determination. If the regression equations predict the responses better and the fittings are proper, then R-Sq values come closer to 100%. An equation with R-Sq value of 90% can demonstrate 90% of the variability in the dependent parameters.

4.4 Graphical Analysis

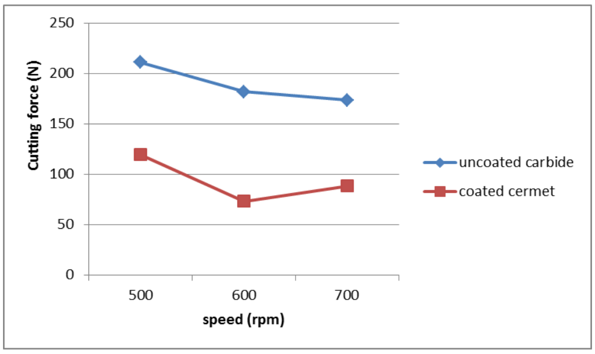


Fig. 4.2 (a): Plot of cutting force vs spindle speed

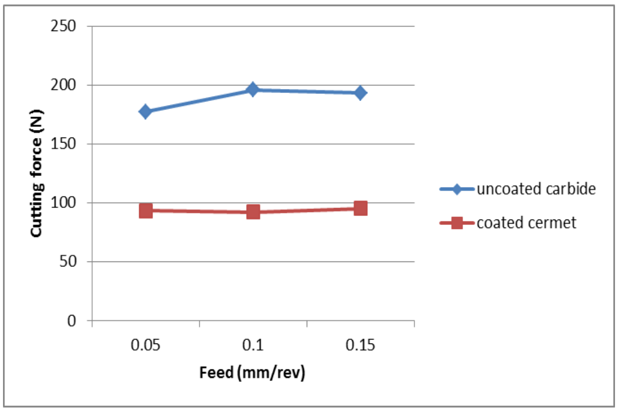


Fig. 4.2 (b): Plot of cutting force vs feed

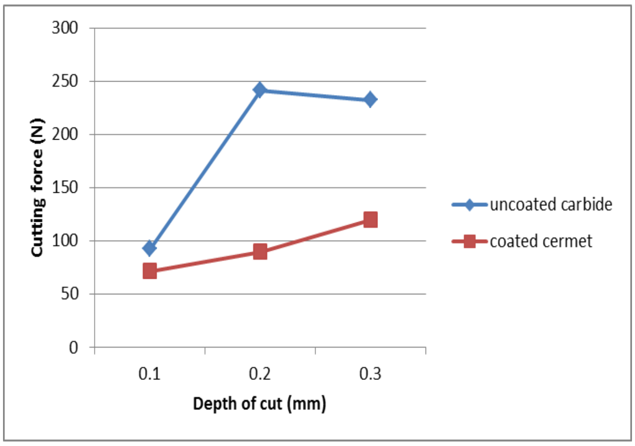


Fig. 4.2 (c): Plot of cutting force vs depth of cut

Fig. 4.2 differentiates the cutting force experienced by uncoated carbides from that by coated cermets which is lesser. There is a decrease in cutting force when speed changes from 500 to 600 rpm. But it again increases for cermets up to 700 rpm. Thecutting force remains almost constant with feed for cermets, but enhances slightly for carbides from 0.05 mm/rev to 0.1 mm/rev feed. There is a drastic increase in cutting force for carbides from the depth of cut 0.1 to 0.2 mm, but then decreases slightly. However, a steady increase in the cutting force using cermets can be observed.

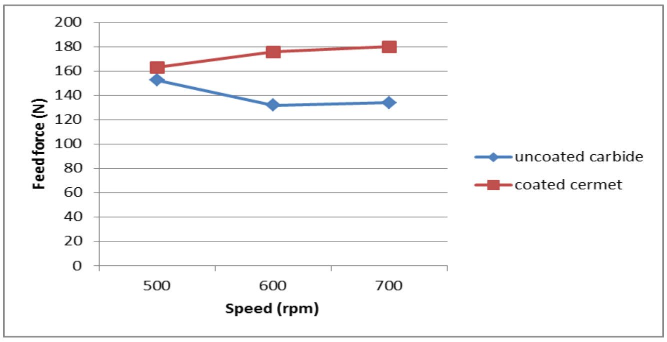


Fig. 4.3 (a): Plot of feed force vs spindle speed

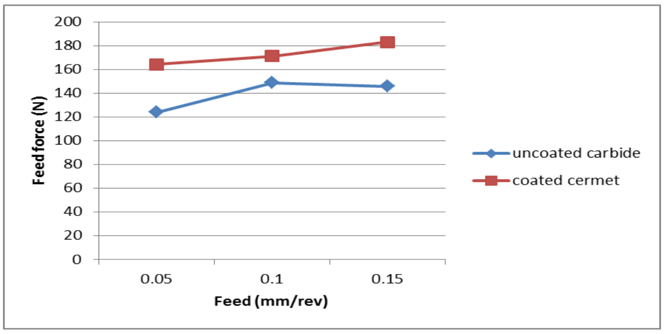


Fig. 4.3 (b): Plot of feed force vs feed

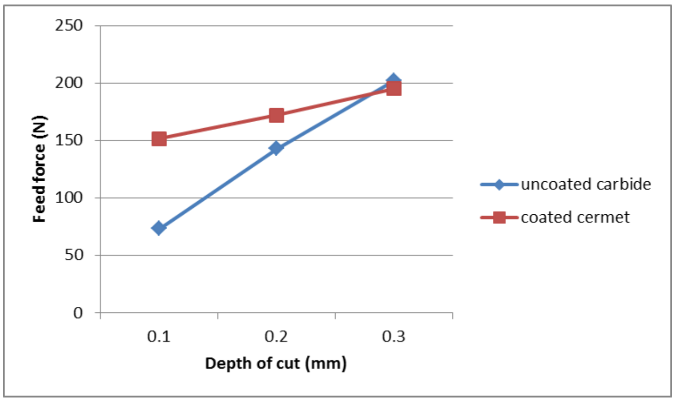


Fig. 4.3 (c): Plot of feed force vs depth of cut

From Fig. 4.3, it is noticed feed force by cermets are generally more than that by carbides except at depth of cut of 0.3 mm. Carbide and cermet inserts behave differently from 500 to 600 rpm. Feed force becomes greater for cermets where it is opposite for carbides. There is a slight increment of feed force with feed for cermets. Though, there is a minimal reduction for carbides in the feed range of 0.1 to 0.15 mm/rev. A linear trend can be seen for both inserts with the depth of cut, where the rate of increment is greater for carbides.

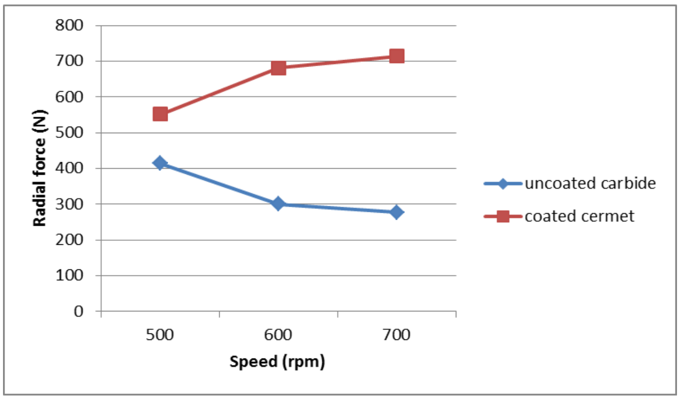


Fig. 4.4 (a): Plot of radial force vs spindle speed

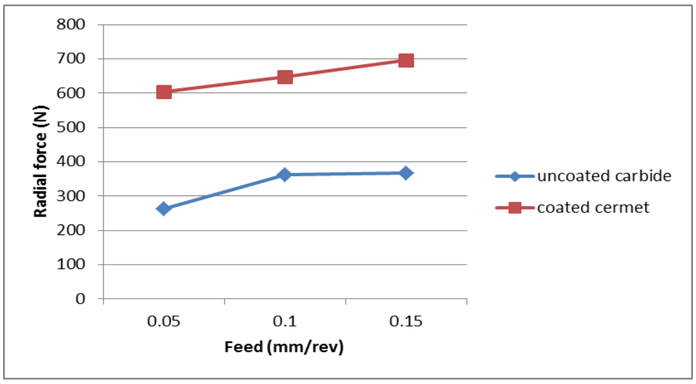


Fig. 4.4 (b): Plot of radial force vs feed

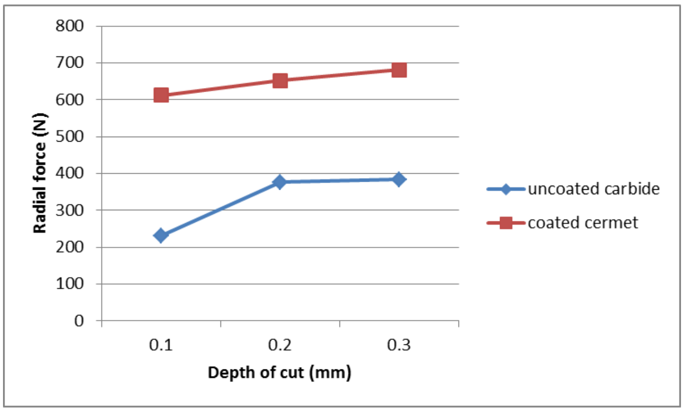


Fig. 4.4 (c): Plot of radial force vs depth of cut

Like feed force radial force is higher in case of cermets as shown in Fig. 4.4. With spindle speed radial force gets larger for cermets, and the effect is reversed for carbides. Radial force rises linearly with the effect of feed and depth of cut. At the same time, radial force first increases then become nearly stable for the carbides.

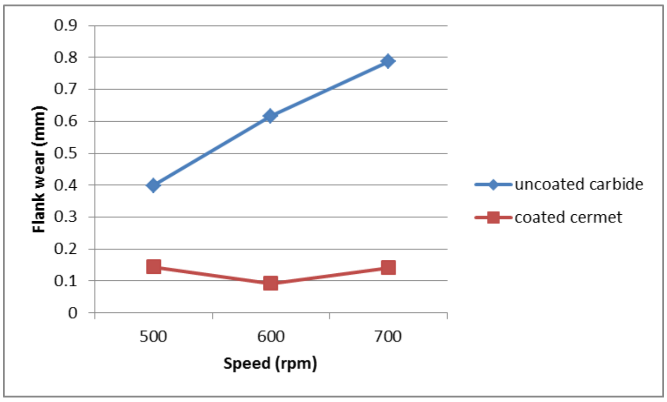


Fig. 4.5 (a): Plot of flank wear vs spindle speed

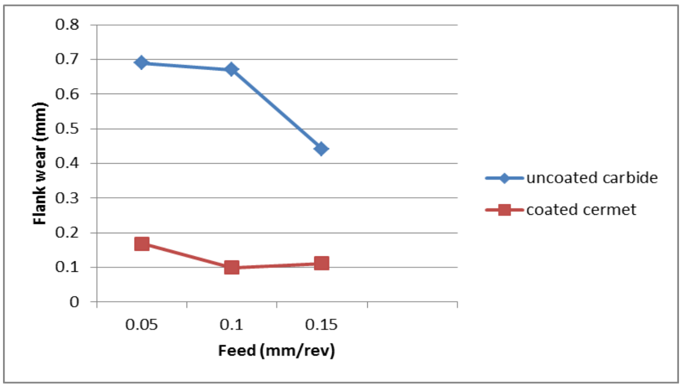


Fig. 4.5 (b): Plot of flank wear vs feed

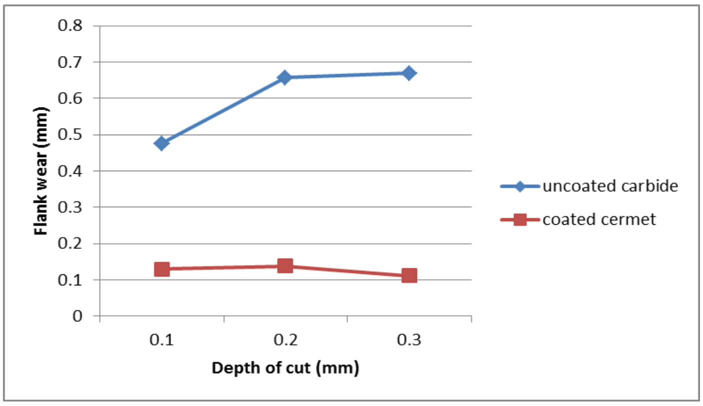


Fig. 4.5 (c): Plot of flank wear vs depth of cut

Fig. 4.5 confirms that flank wear of carbides is more than that of cermets. Flank wear of the carbides is uniformly rising with speed. Considering cermets, the wear on the flank surface drops and then increases. Between the feed range of 0.05 to 0.1 mm/rev, there is similar nature of decline in flank wear for both tools. After that there is a radical decrement in the flank wear of carbide inserts, wherever flank wear of cermets becomes almost same. The depth of cut does not seem to have substantial effect on the flank wear of coated cermets, even if it increases up to the depth of cut 0.2 mm for uncoated carbides.

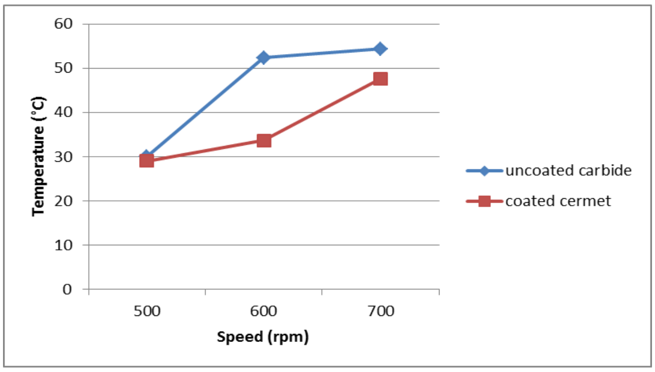


Fig. 4.6 (a): Plot of temperature vs spindle speed

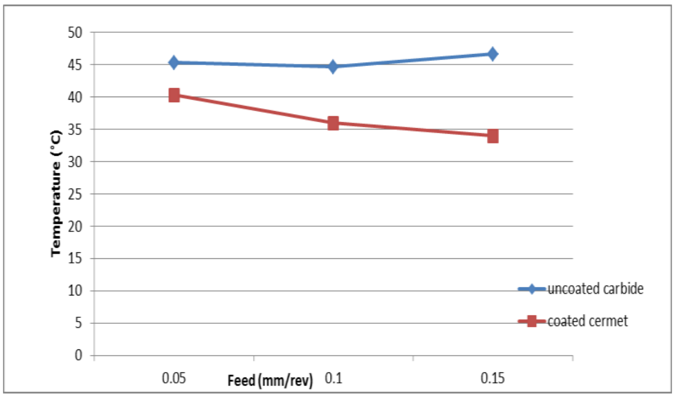


Fig. 4.6 (b): Plot of temperature vs feed

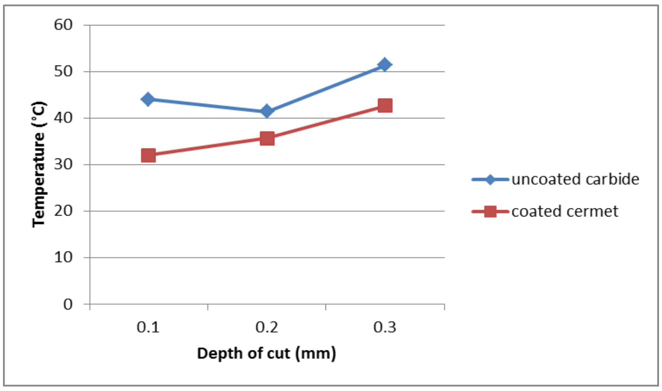


Fig. 4.6(c): Plot of temperature vs depth of cut

Workpiece surface temperature developed during the use of carbide tools remains above that of cermets, which is evident from Fig. 4.6. Still the temperatures at the spindle speed of 500 rpm are quite near for both the inserts. There is a negligible alteration in workpiece surface temperature, while carbide being considered. Slight fall in temperature follows cermet with feed. Temperature of the specimen is elevated using coated cermets with the depth of cut, whereas the trend is similar from 0.2 mm up to 0.3 mm depth of cut working with carbides.

4.5 Multi-response Optimization with Grey Relational Grade (GRG)

After getting the experimental results of F_x, F_y, F_z, VBc, T; values of quality loss function, Grey relational coefficients and Grey relational grades have been calculated according to Equations (1), (2) and (3) and are tabulated in tables 4.13 and 4.14 for uncoated carbides and 4.16 and 4.17 for coated cermets. For calculating Overall Grey Relational Grade we have given 0.35 weightage to each of cutting force and flank wear and 0.1 weightage to each of feed force, radial force and workpiece surface temperature. It is because cutting force and flank wear are the main controlling factors of the machining aspects.

4.5.1 Uncoated Carbides

Grey Relational Analysis for the machinability aspects using uncoated carbide inserts is done below.

Table 4.13: Normalized values of output responses and quality loss function

Run	Normalized Values					Quality Loss function				
	F_z	F_x	F_y	VBc	T	F_z	F_x	F_y	VBc	T
1	0.903	1.000	0.884	0.996	0.943	0.097	0.000	0.116	0.004	0.057
2	0.000	0.375	0.051	0.685	1.000	1.000	0.625	0.949	0.315	0.000
3	0.054	0.000	0.000	0.968	0.629	0.946	1.000	1.000	0.032	0.371
4	0.249	0.664	0.765	0.227	0.314	0.751	0.336	0.235	0.773	0.686
5	0.205	0.125	0.418	0.358	0.114	0.795	0.875	0.582	0.642	0.886
6	0.973	0.987	0.915	1.000	0.229	0.027	0.013	0.085	0.000	0.771
7	0.351	0.270	0.827	0.000	0.000	0.649	0.730	0.173	1.000	1.000
8	1.000	0.947	1.000	0.276	0.200	0.000	0.053	0.000	0.724	0.800
9	0.216	0.520	0.497	0.472	0.286	0.784	0.480	0.503	0.528	0.714

Table 4.14: Grey relational coefficients for output responses and overall GRG

Run	**Grey Relational Coefficient**					**Overall Grey Relational Grade**
	F_z	**F_x**	**F_y**	**VBc**	**T**	
1	0.838	1.000	0.812	0.992	0.898	0.912
2	0.333	0.444	0.345	0.613	1.000	0.510
3	0.346	0.333	0.333	0.940	0.574	0.574
4	0.400	0.598	0.680	0.393	0.422	0.448
5	0.386	0.364	0.462	0.438	0.361	0.407
6	0.949	0.975	0.855	1.000	0.393	0.904
7	0.435	0.407	0.743	0.333	0.333	0.417
8	1.000	0.904	1.000	0.408	0.385	0.722
9	0.389	0.510	0.499	0.486	0.412	0.448

Table 4.15: ANOVA of GRG with uncoated carbide at significance level of 5%

Source	**DF**	**SS**	**MS**	**F**	**P**
Speed	2	0.028115	0.014057	20.75	0.046
Feed	2	0.013735	0.006867	10.14	0.090
Depth of cut	2	0.286788	0.143394	211.67	0.005
Residual error	2	0.001355	0.000677		
Total	8	0.329992			

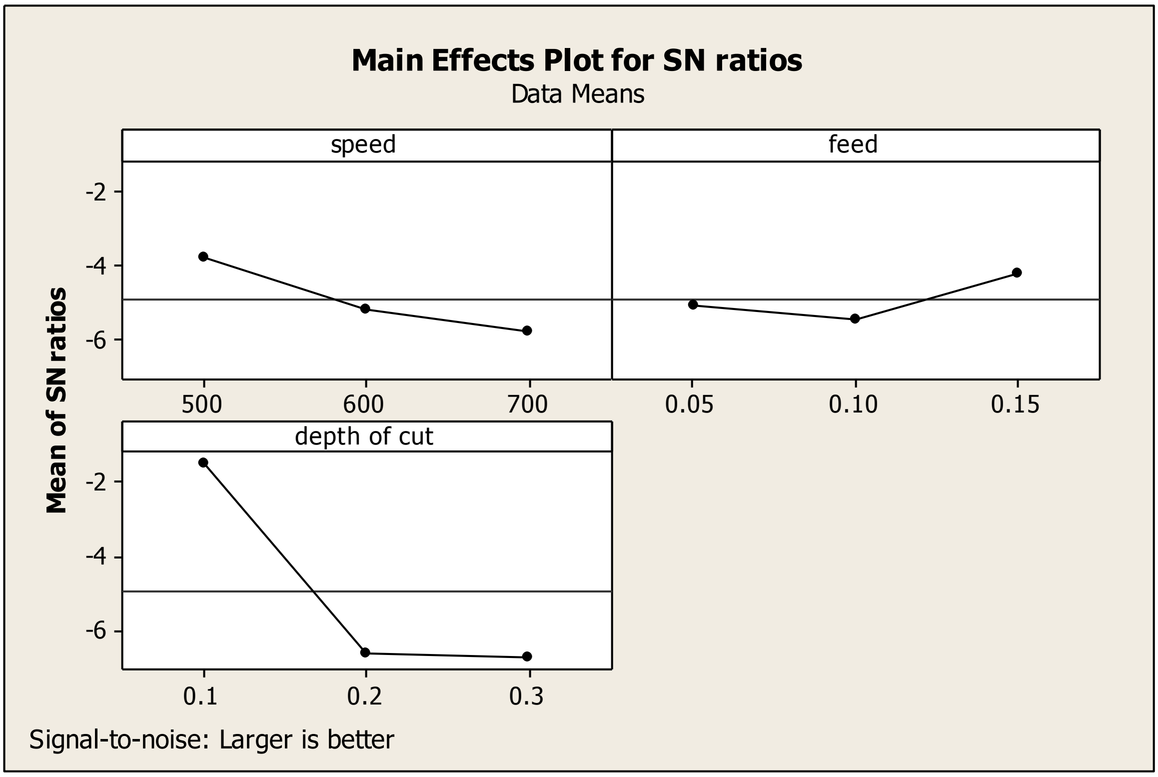


Fig. 4.7: Main effects plot for S/N ratios for uncoated carbide

It has been seen from the table that run number one is having highest grey relational grade 0.912. From ANOVA table it has been concluded that depth of cut is the most significant parameter on Grey Relational Grade followed by cutting speed and feed as found out from Table 4.15. Fig. 4.7 depicts the main effect plot of S/N ratios which shows the optimal settings of input parameters. The optimal conditions according to Grey relational Taguchi approach has been found 500 rpm speed, 0.15 mm/rev feed and 0.1 mm depth of cut for uncoated carbides.

4.5.2 Coated Cermets

Grey Relational Analysis for the machinability aspects using coated cermet inserts is done below.

Table 4.16: Normalized values of output responses and quality loss function

Run	Normalized Values					Quality Loss function				
	F_z	F_x	F_y	VBc	T	F_z	F_x	F_y	VBc	T
1	0.530	1.000	1.000	0.000	0.935	0.470	0.000	0.000	1.000	0.065
2	0.390	0.594	0.615	0.438	0.968	0.610	0.406	0.385	0.562	0.032
3	0.000	0.000	0.388	0.589	0.806	1.000	1.000	0.612	0.411	0.194
4	0.780	0.453	0.360	0.365	0.677	0.220	0.547	0.640	0.635	0.323
5	0.520	0.016	0.163	1.000	0.581	0.480	0.984	0.837	0.000	0.419
6	1.000	0.531	0.191	0.796	1.000	0.000	0.469	0.809	0.204	0.000
7	0.390	0.078	0.154	0.148	0.000	0.610	0.922	0.846	0.852	1.000
8	0.820	0.594	0.249	0.569	0.484	0.180	0.406	0.751	0.431	0.516
9	0.640	0.125	0.000	0.373	0.419	0.360	0.875	1.000	0.627	0.581

Table 4.17: Grey relational coefficients for output responses and overall GRG

Run	Grey Relational Coefficient					Overall Grey Relational Grade
	F_z	F_x	F_y	VBc	T	
1	0.515	1.000	1.000	0.333	0.885	0.585
2	0.450	0.552	0.565	0.471	0.940	0.528
3	0.333	0.333	0.450	0.549	0.720	0.459
4	0.694	0.478	0.439	0.441	0.608	0.550
5	0.510	0.337	0.374	1.000	0.544	0.654
6	1.000	0.516	0.382	0.710	1.000	0.698
7	0.450	0.352	0.371	0.370	0.333	0.393
8	0.735	0.552	0.400	0.537	0.492	0.590
9	0.581	0.364	0.333	0.444	0.463	0.475

It has been seen from the table that run number six is having highest grey relational grade 0.698.

Table 4.18: ANOVA of GRG with coated cermet at significance level of 5%

Source	DF	SS	MS	F	P
Speed	2	0.035448	0.017724	14.09	0.066
Feed	2	0.009995	0.004997	3.97	0.201
Depth of cut	2	0.026589	0.013294	10.57	0.086
Residual error	2	0.002517	0.001258		
Total	8	0.074548			

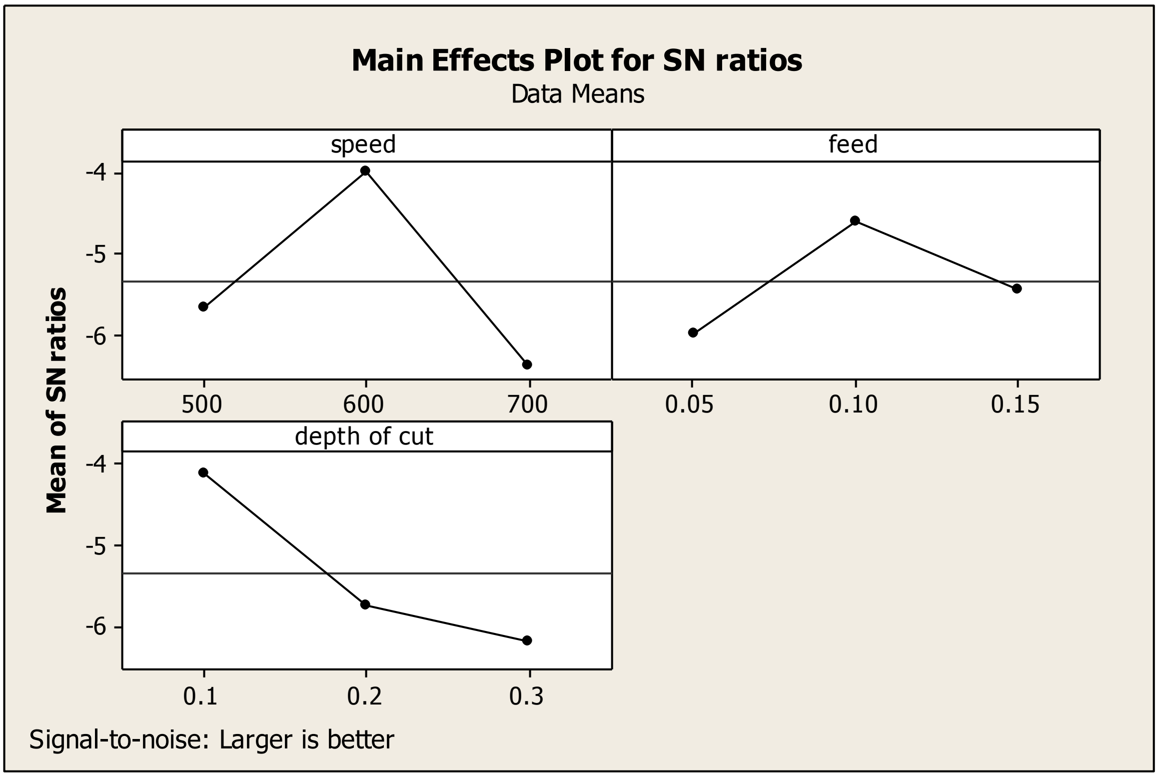


Fig. 4.8: Main effects plot for S/N ratios for coated cermet

From ANOVA table it has been concluded that speed is the most significant parameter on Grey Relational Grade followed by cutting depth of cut and feed (Table 4.18). Fig. 4.8 depicts the main effect plot of S/N ratios which shows the optimal settings of input parameters. The optimal conditions according to Grey relational Taguchi approach has been found 600 rpm speed, 0.1 mm/rev feed and 0.1 mm depth of cut for coated cermets.

4.6 Discussion of thermal aspects

According to Davim [30], a non-dimensional entity called Peclet number is helpful to study the impact of heat energy in hard machining. It can be expressed in terms of cutting speed, feed and thermal diffusivity of test material as

$$Pe = (v \times f) / \alpha \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Speed, feed has supremacy over thermal properties of the work material in influencing the temperature when Pe>10. If Pe< 10, properties of the specimen are predominant over cutting regime. The value of thermal diffusivity of AISI 4340 steel is calculated to be 1.181×10^{-5} m^2/s.

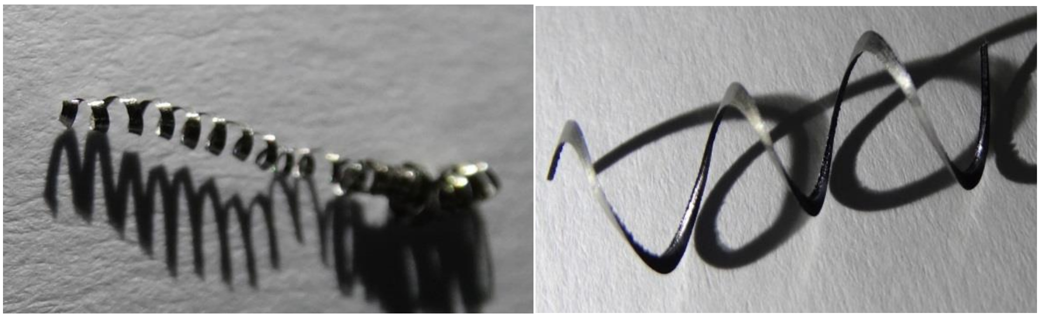
Table 4.19: Peclet number for both inserts

Run No	Peclet number for uncoated carbide	Peclet number for coated cermet
1	5.535	5.052
2	11.134	10.084
3	16.360	14.898
4	6.481	5.890
5	12.861	11.670
6	18.926	17.288
7	7.307	6.676
8	14.460	13.182
9	21.452	19.633

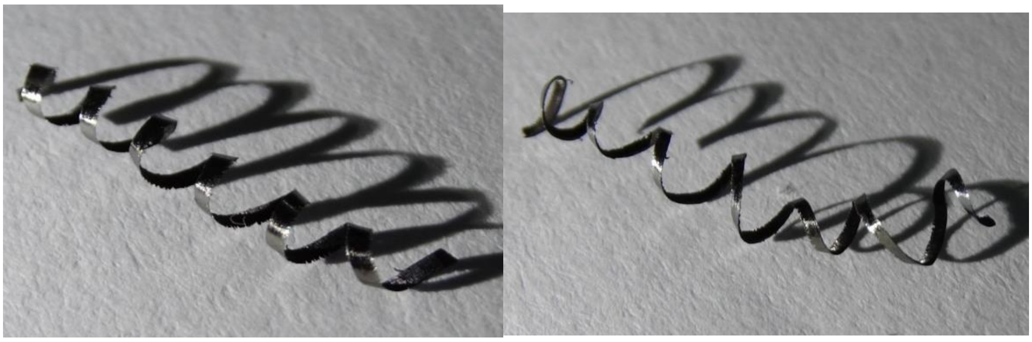
We can draw the conclusion from the Table 4.19, Pe is less than 10 only when feed value is 0.05 mm/rev, other than that Pe goes beyond 10.

4.6.1 Effect of chip morphology on temperature

Experimental runs with carbide created chips of light golden shading and it is of helical continuous type as shown in Fig. 4.9.

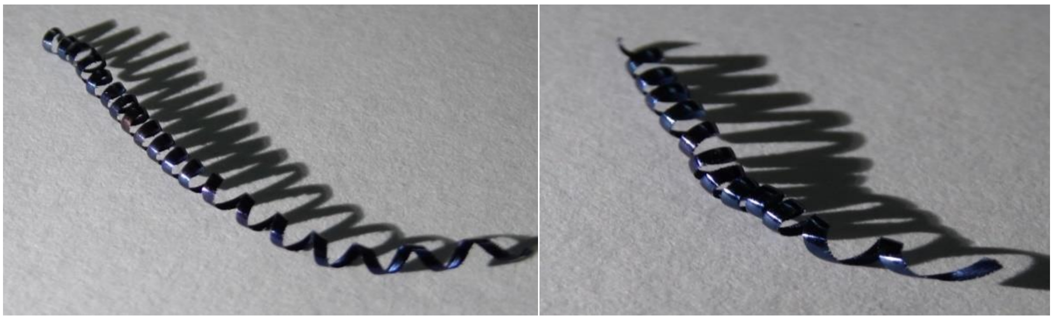


(a) **(b)**

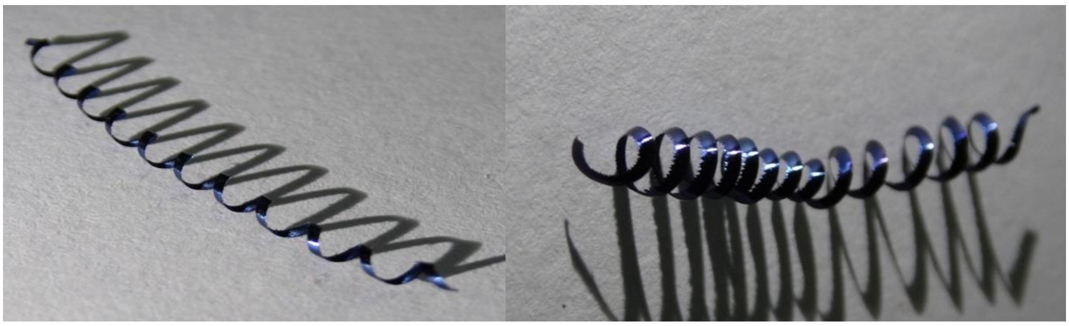


(c) **(d)**

Fig. 4.9: Chip produced with uncoated carbide insert



(a) **(b)**



(c) **(d)**

Fig. 4.10: Chip produced with coated cermet insert

The light golden colored chip yielded when there was friction between the insert and work material. So it influences the tool life and additionally cutting temperature amid the machining operation. At whatever point pale blue colored chips delivered in machining, it implies sufficient heat is expelled from the workpiece. We can see blue shading chips and their class from Fig. 4.10 while machining the specimen with coated cermets.

A lower temperature was observed with cermets as compared with carbides in machining AISI 4340 steel. Cutting speed is the main component for heat generated in any machining operation. From Fig. 4.6(a) it is proved that in the event of both carbide and cermet temperature is expanding with speed, it is essentially because of the non- accessibility of time for heat exchange to surroundings.

4.7 Discussion of machining forces

The insert geometry has a great effect on the cutting constraints in turning operation. A square insert gives additionally cutting force contrasted with rhombic insert. The square insert with point edge of 90 degree is robust and tougher than diamond or rhombic shape insert having 80 degree point edge. Hence it obliges more power or cutting force amid machining and delivers additionally cutting power.

Likewise in a higher point edge angle the bigger forefront will be in contact with the workpiece coming about more force and temperature in carbides which is upheld by Figs. 4.2 and 4.6. Because of higher machining power and temperature both mechanical and thermal load is dominating on carbides. Subsequently, there is edge depression and crest and trough arrangement on the flank surface of this supplement because of plastic disfigurement. Subsequently, carbide inserts get to be effectively worn out in comparison with cermet and obliges more cutting force.

For carbides and cermets entering or approach angle gave by their particular holders are 75 and 95 degree. As a purpose behind little approach angle there was an inclination of vibration while machining with carbides, so it has been discovered to be more temperamental. Because of this insecurity, cutting force and flank wear both were hampered for carbides. Accordingly, a higher temperature is produced.

Because of the spring back impact of work material, radial force is dominating over cutting force for both inserts. With the advancement in flank wear, the distinction in between radial and tangential force is expanded.

Tungsten carbide is generously harder and has more scratch resistance than the Titanium coated cermet because of the dense structure. As an outcome, the radial force recorded is more for cermets than carbides.

4.8 Effects of chip breaker geometry

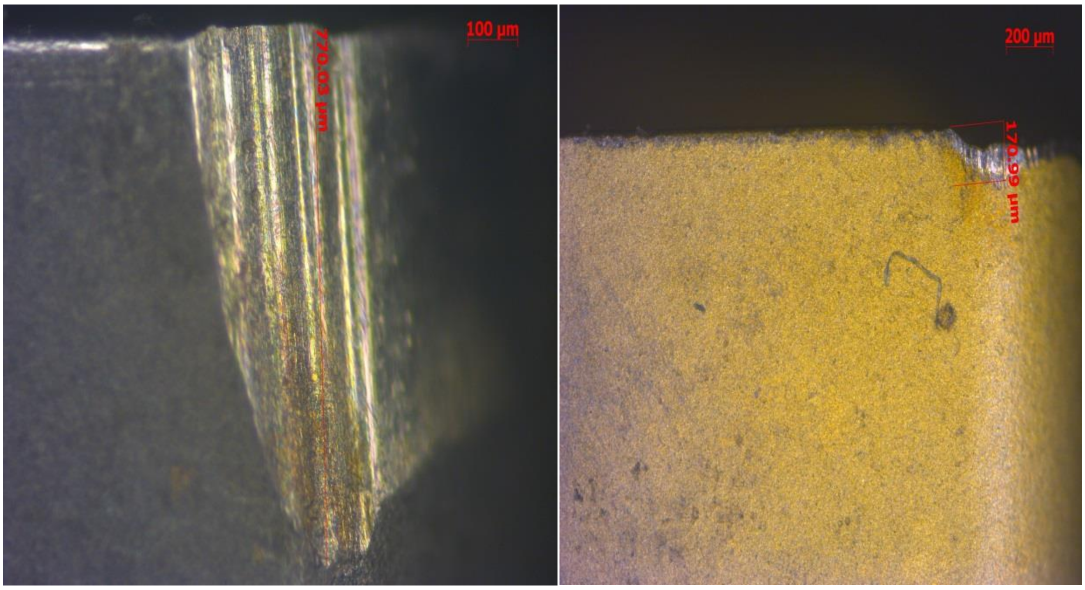
The inserts utilized as a part of the present examinations have two sorts of chip breaker geometry. The uncoated carbide additions are having no particular kind of chip breaker, yet coated cermets have fine finishing geometries. Effects of having chip breaker geometry are described below

Controlled contact length exists in the middle of chip and insert, accordingly there was less wear and rubbing in cermets. Better heat dissemination to the chip was attained making it blue shaded. It influences in decreasing temperature and cutting force for coated cermets.

Crater wear of the cermet inserts were lesser as an aftereffect of the vicinity of chip breaker geometry. Anyhow crater wear surfaced on carbides which are apparent from Fig. 4.13.

4.9 Tool wear analysis

In the present study different varieties of tool wear were seen like crater and flank wear, chipping, built-up edge formation, notch, plastic deformation, chip hammering, development of crest and trough and so forth.



(a) Uncoated carbide **(b)** Coated cermet

Fig. 4.11: Flank wear measurement

Flank wear happens because of abrasion, vicinity of hard constituents called inclusions in the workpiece material. In this kind of wear little bits of coating break-off furthermore enters into the substrate material. Flank wear is shaped at high speed in low wear resistant grades of inserts. Flank wear measurement is shown in Fig. 4.11 and SEM image of flank wear in the cermet insert is shown in Fig. 4.12.

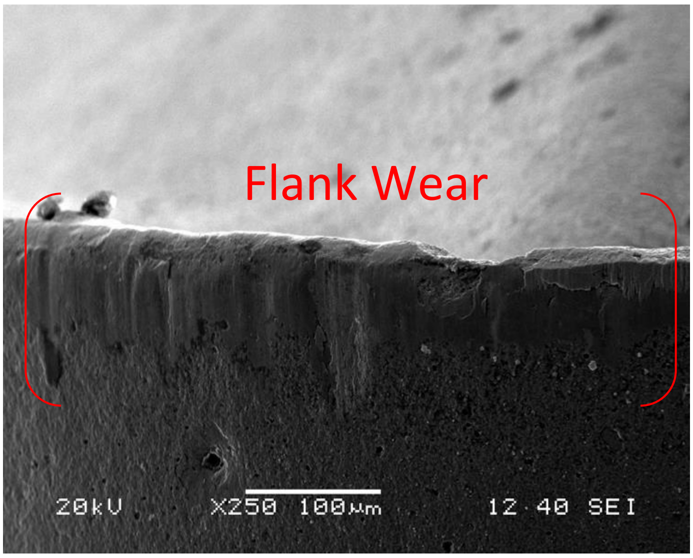


Fig. 4.12: SEM image of flank wear in coated cermet

Crater wear is limited to the rake side of the insert. It is because of diffusion, decay, abrasion and adhesion between the workpiece material and cutting tool. It is enhanced by the tool material and flawed chip breaker geometry, which is the reason it is more noticeable in uncoated carbides. Hard and hot chips break down the binder and disintegrate the substrate in crater wear.

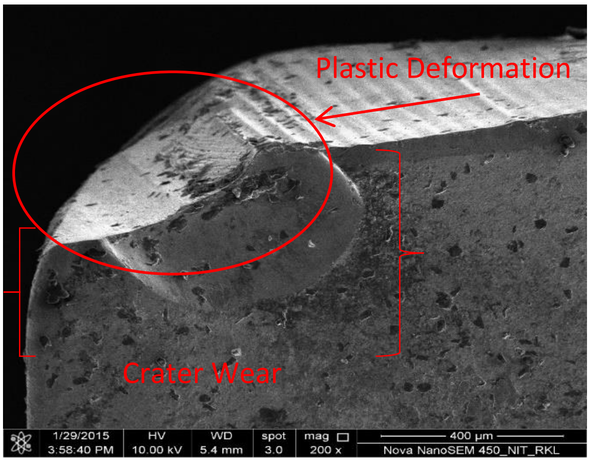


Fig. 4.13: SEM image of crater wear and plastic deformation in uncoated carbide

Plastic distortion takes place when the cutting material softens because of mechanical and thermal over-burdening. It happens when the cutting temperature is too high for the insert to withstand. The inserts misshape, cutting edge is depressed as a consequence of the softening of the binder material. It occurs while machining at high cutting speed and feed without the utilization of cutting fluid. An SEM image is given in Fig. 4.13 to show the crater wear and plastic deformation of uncoated carbide.

Chipping is a kind of flank wear, which is happened because of local stress concentration, hard micro incorporation exhibit in the workpiece and shaky machining environment. Vibration, built-up edge causes this local stress focus in machining. High velocity and low feed escalates chipping phenomenon which can be seen from Figs. 4.14 and 4.15.

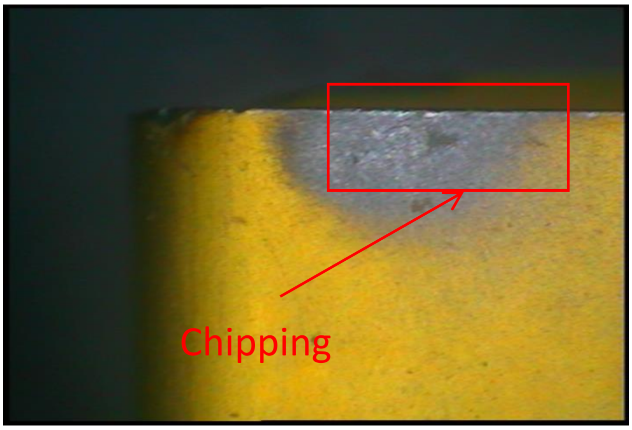


Fig. 4.14: Chipping in coated cermet

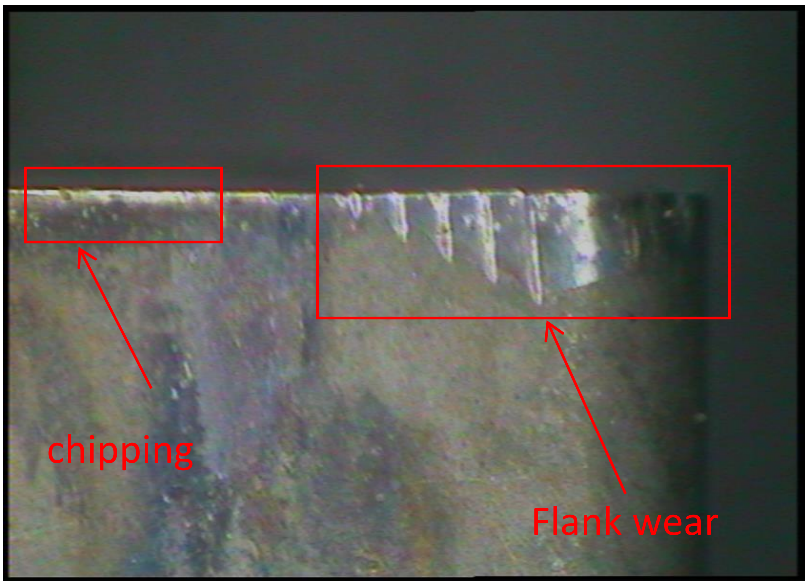


Fig. 4.15: Chipping in uncoated carbide

The mechanism of built-up edge formation is the material adhesion at a high pressure and low temperature bringing about pressure welding of the hard chip to the tool. Then this built-up edge severs and takes bits of the coating and substrate with it. It is most basic when machining with an insert with negative rake angle at low cutting speed and low feed. Figs. 4.16 and 4.17 show the images of built-up edges formed on a carbide insert and cermet insert respectively.

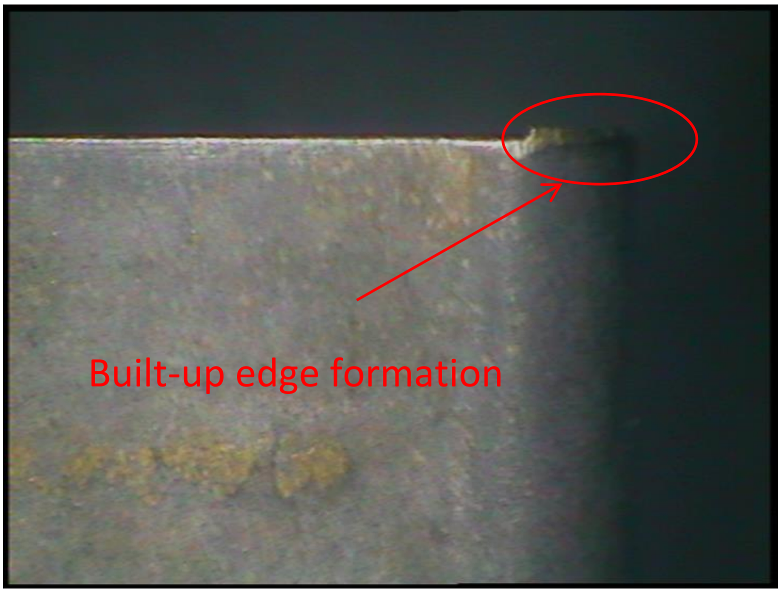


Fig. 4.16: Built-up edge formation in uncoated carbide

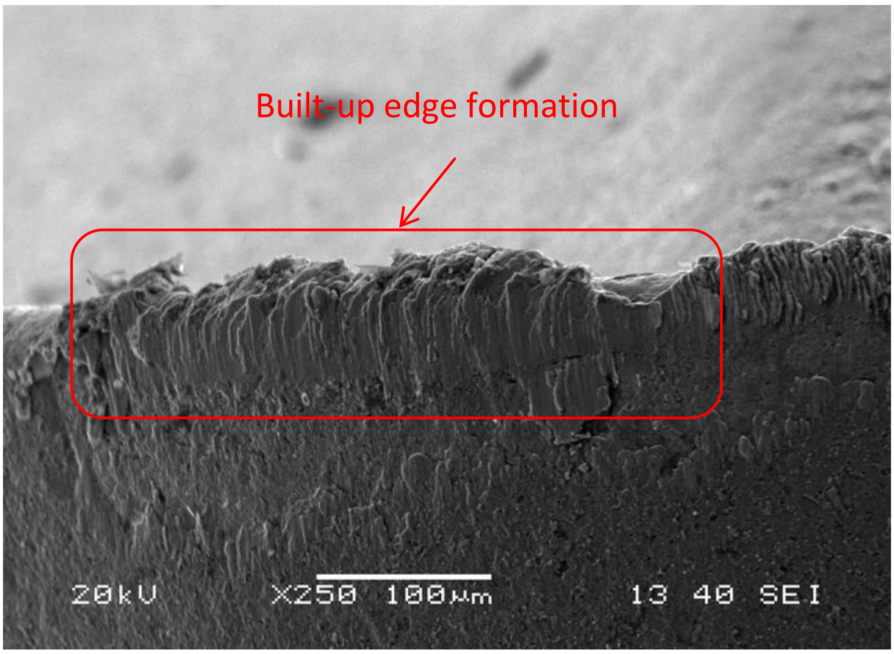


Fig. 4.17: SEM image of built-up edge formation in coated cermet

Notching is a sort of flank wear which is formed at the cutting edge. It generally relies on oxidation of machining surface, local stress fixation at the flank face, hard micro incorporation in workpiece and surface hardening of the workpiece in the past run. Notch wear happens when machining sticky materials with less harder evaluations of inserts having high negative rake and approach angle at high speed and feed. SEM image of notch wear and chipping of coated cermet can be seen from Fig. 4.18.

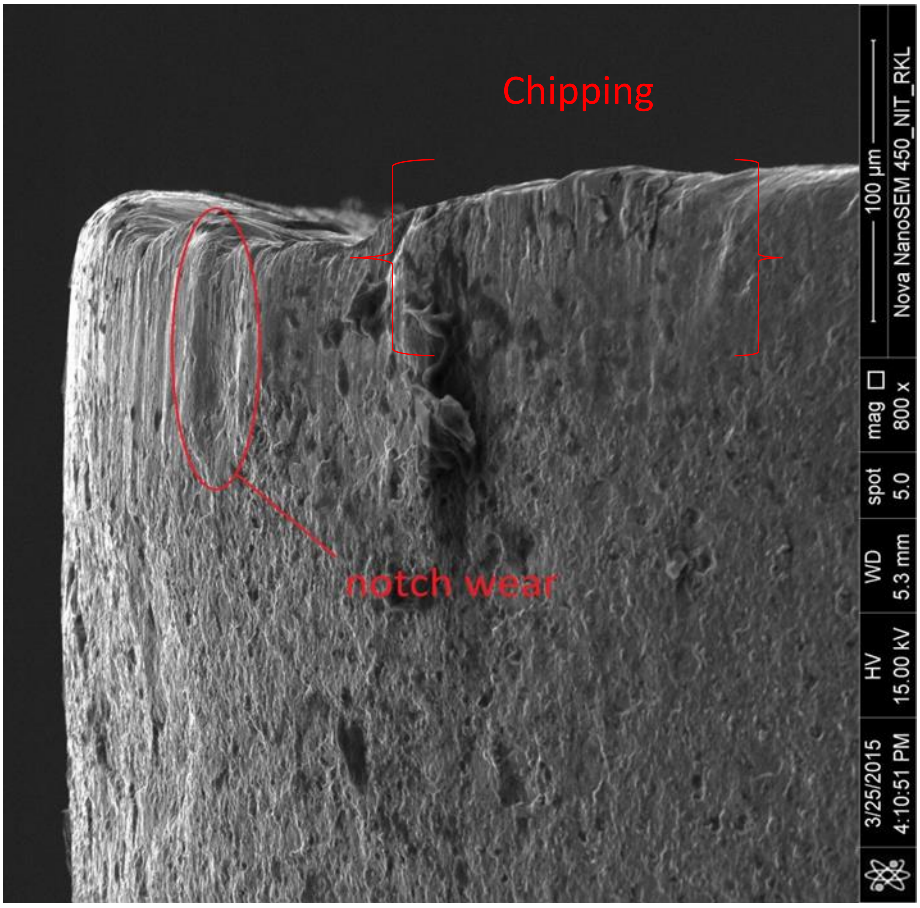


Fig. 4.18: SEM image of notch wear and chipping in coated cermet

Chip hammering is a kind of abrasive wear which happens when the chip crashes into the cutting edge and harm it. So it is mainly evident when machining materials having long chipping qualities. It is additionally helped by high feed and depth of cut, despicable approach angle and incapable chip breaker geometry. This phenomenon is given in the Fig. 4.19 of uncoated carbide.

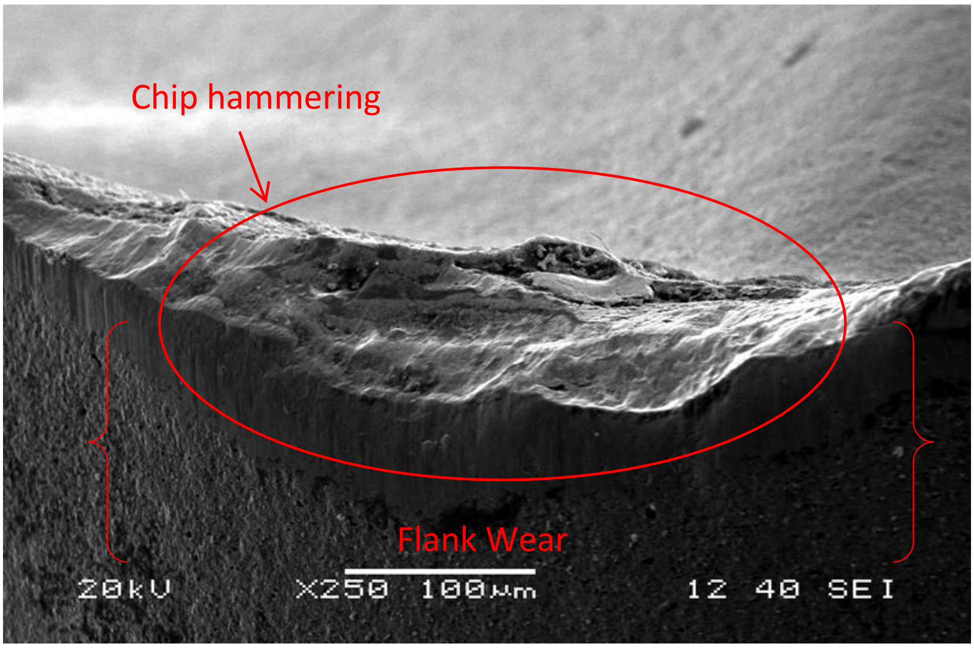


Fig. 4.19: SEM image of chip hammering and flank wear in uncoated carbide

After the procedure of heat treatment, the martensitic structure of steel was attained to with hard inclusions. Because of this, the material is expelled from the flank surface when tool moves over the workpiece and the state of peak and trough is framed. Titanium coated cermet has a superior crack resistance than that of tungsten carbide. Consequently, this sort of wear was not framed in cermets. Crest and trough formation in uncoated carbide is presented in Fig. 4.20.

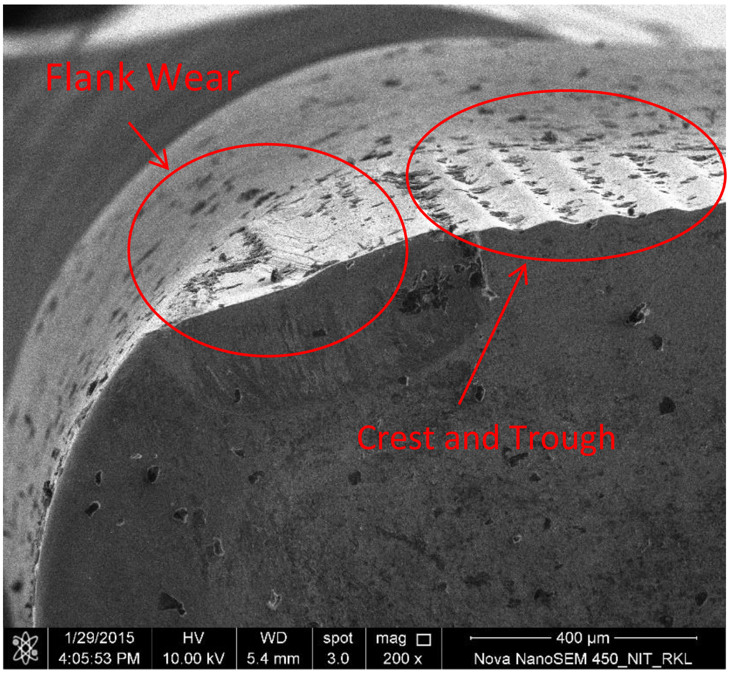


Fig. 4.20: Crest and trough formation in uncoated carbide

The uncoated carbide contains tungsten carbide, which is 83% of the total normalized weight and 5.40% cobalt which acts as a binder. As indicated by this measurements grain structure of carbide inserts are medium coarse (2.1-3.4 micron). However, the cermets are of a fine grain structure and exhibits longer tool life.

4.10 Effect of coating on tool life

Different sorts of coatings can be requisitioned for the upgradation of tool life on the substrate i.e. Titanium nitride, Titanium carbo nitride, Titanium aluminium nitride, Zirconium nitride, Diamond coating and so on. These coatings may be applied either PVD or CVD technique. Yet thickness is the most critical criteria of coating. Wherever the inserts are brittle, cracking and failures may happen if the thickness of coating is high. The cermet grades used for our experiment were of coating thickness 2-3 μm.

Coating of TiN gives better resistance to abrasive wear by keeping the built-up edge formation in check. It additionally averts sticking of the workpiece to the cutting inserts. Along with these, crater wear is constrained and there is an increase in tool life. TiN coating can likewise bring down the coefficient of friction of the insert surface making the force experienced and temperature generated lesser. Also, TiN coatings assume critical part when the high temperature is included in machining. It keeps up the chemical stability of the insert at high temperature while acting as a thermal hindrance. Additionally, it opposes the oxidation and diffusion. TiCN coating provides the insert with good adhesion and bonding strength. As a result, we have witnessed lesser wear; workpiece surface temperature involved with coated cermet inserts which were less worn-out.

Carbide inserts get to be weaker because of the absence of coating. They generally fizzle because of progressive wear created by cobalt binder dissemination and disintegration of free tungsten carbide stage and complex carbide particles.

CHAPTER 5

CONCLUSION

The following conclusions are drawn out of the results obtained from the present work.

1. Coated cermets outperform uncoated carbides with respect to cutting force, flank wear and workpiece surface temperature whereas uncoated carbides outperform in case of feed force and radial force.

2. The depth of cut is the most significant parameter for feed force as well as radial force in case of both coated cermets and uncoated carbide whereas spindle speed is most significant only for uncoated carbides. Yet for cermets, cutting force is mostly managed by the speed which additionally governs temperature primarily. Flank wear of carbides and cermets are influenced by speed and feed respectively.

3. The optimum spindle speed, feed and depth of cut level of machining uncoated carbide are 500 rpm, 0.15 mm/rev and 0.1 mm respectively. But it is possible to use higher spindle speed while using cermet tools. The corresponding optimum level are 600 rpm speed, 0.1 mm/rev feed and 0.1 mm depth of cut.

4. Coating has a positive effect on the performance of inserts because of which tool wear, cutting force and temperature are less when coated cermets are utilized rather than uncoated carbides.

5. Peclet number mostly varies with feed and not that much with speed.

6. Hard machining usually creates saw-tooth chips. We have got serrated chip of consistent nature for both carbides and cermets as the specimen hardness was 48HRC.

7. Flank wear is the prevalent sort of wear in case of both the inserts. Distinctive types of flank wear viz. chipping, notching etc. were noticed while examining with both SEM and advanced optical microscopic images.

FUTURE SCOPE OF WORK :

Machining of hardened steel comprises a vast field to research upon, among which a small area has been chosen during my project. It is to be believed there will be immense scope of work at this same field. Several such areas which might seem to be interesting for future researchers are shared below.

- There are many other machinability aspects like surface finish, torque, chip reduction coefficient, chip morphology, power consumption and material removal rate.
- Uncoated and coated cermet inserts have been used by many researchers, but effect of cryogenic cycle by changing different cryo-treatment parameters like cooling rate, heating rate, holding time, initial and final temperature on the tool life of different cutting inserts has not been studied substantially.
- The experimental runs were carried in dry cutting environment, whereas effects of various cutting fluids and various cooling techniques on the performance of cermet inserts have not been investigated enormously. Now-a-days use of coolants has been discouraged due to its adverse effects on environment. So, there is a chance to research upon the effect of Minimum Quantity Lubrication (MQL) on the machinability aspects.
- Statistical optimization techniques have been proposed by many researchers, but advanced optimization methods like, Genetic Algorithm, Simulated Annealing and Particle Swarm Optimization etc. have not been employed in a large scale. Also, there was limited amount of work using other Multi-response optimization techniques like Utility and Desirability approach etc.
- There is a scope of modelling maximum principal stress, maximum shear stress, deformation etc. on the cutting inserts in machining using software like ANSYS.

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